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TECHNICAL NOTE

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THE EFFECT OF FUEL COMPOSITION, COMPRESSION PRESSURE, AND FUEL-AIR RATIO ON THE COMPRESSION-IGNITION CHARACTERISTICS OF SEVERAL FUELS

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SUMMARY

A rapid compression machine developed at the Massachusetts Institute of Technology under the sponsorship of the National Advisory Committee for Aeronautics was used to determine the variation in ignition delay and rate of pressure rise after compression for four fuels; namely, isooctane, 100-octane gasoline, triptane, and benzene. The tests were conducted with fuel-air ratio and compression ratio as the only independent variables. The essential feature of the present paper is a study of the pressure-time relations during the preliminary phases of a spontaneous explosion.

The photographic records obtained suggest an explanation as to why fuels like benzene and triptane fail to detonate in an engine under conditions which cause isooctane to detonate severely. The records also indicate that a comparison of the detonating tendencies of two fuels must include not only a consideration of the length of the delay period, but also an evaluation of the rate of pressure rise after compression.

Tests to determine the effect of humidity, dust, and surface action on the ignition delay of isooctane are also described. The results indicate that, except when the cylinder walls are coated with lubricating oil, no decided change is produced.

In many cases there was considerable variation in the delay and combustion rate in spite of the careful control exercised to keep operating conditions constant. These variations have not yet been explained. This same difficulty has been encountered in previous work along the same lines. In the present work the uncertainty occasioned by these variations was lessened by making a sufficient number of runs to obtain a fair average.

INTRODUCTION

An understanding of the pressure-temperature-time events immediately preceding the spontaneous explosion of a gaseous mixture is of great importance in leading toward a better understanding of the mechanism of detonation in the internal-combustion engine. These events are usually referred to as preliminary reactions and originate, in the case of engine operation, in the end gas, or last part of the charge to burn. The immediate cause of these reactions is the rapid compression of the end gas by the expanding gases behind the flame front in conjunction with the upward movement of the piston. The time interval during which these preliminary reactions become manifest is known as the "ignition delay" or "delay period," and the whole process from inception to explosion is known as the phenomenon of self-ignition or autoignition.

It is difficult to study the self-ignition process in an internal-combustion engine because the presence of many variables renders the isolation and measurement of the phenomenon extremely inconvenient. The phenomenon is most readily studied in an isolated apparatus in which the explosive mixture is subjected to a single rapid adiabatic compression. During the past 40 years several such devices have been built (see appendix A of reference 1) and a phenomenon of great fundamental importance, that is, the ignition delay, has been brought to light. In spite of this important discovery and the welter of new speculation opened thereby, recent efforts along these lines have languished to the extent that few if any such experimental investigations have been pursued in the past 15 years.

The reason for this apparent apathy is not lack of interest in the subject but rather the serious experimental difficulties involved. However, with the multitude of new experimental techniques now available, the way is clear for a mass assault on the problem. The present investigation is a step in this direction.

The problem can be approached in two ways; exploratory or analytical. The exploratory approach involves testing a great many fuels under various conditions of mixture strength, compression ratio, temperature, and so forth,and studying the results more or less qualitatively with a view to unearthing new phenomena, classifying explosion types, and framing new theories. This type of investigation is particularly fruitful with the field in its present undeveloped state. Such an investigation should be pursued in connection with all combustible liquids having possibilities for use in aircraft engines.

The other approach requires a concentration of effort on the production of a few precision test results with a view to testing existing, or formulating new chemical theories. This approach calls for a high degree of refinement in the apparatus.

The present work is exploratory in nature. The records presented herein show the diverse aspects of the autoignition phenomenon and point to the existence of fuels having explosion characteristics as yet unsuspected. It is hoped that these results will stimulate a renewal of activity in this most important branch of combustion research.

This work was conducted at the Massachusetts Institute of Technology under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

APPARATUS

The rapid compression machine used in this work is completely described in reference 1. Details of construction, dimensions, drawings, operating procedures, and the method used to prepare fuel-air mixtures are given in this reference.

EXPERIMENTAL PROCEDURE

Tests were made on isooctane, 100-octane gasoline, triptane, and benzene in order to determine their pressure-temperature-time histories when exploded by a rapid adiabatic compression.

The isooctane (2,2,4 trimethyl pentane) was obtained from a reliable oil company and was designated as S-1 reference fuel from SAE stock. This fuel was about 2 years old but had been kept tightly sealed in a metal container.

The 100-octane gasoline was obtained from a different but equally reliable source and was a sample from a standard batch designated as grade-130 aviation, rated by the C-3 method.

The triptane (2,2,3 trimethyl butane) was obtained from the National Bureau of Standards, through the National Advisory Committee for Aeronautics, in a sample of 600 cubic centimeters.

The benzene was obtained from the M.I.T. laboratory stock of pure benzene.

These fuels were tested under the conditions of variable compression ratio or variable fuel-air ratio with all other conditions held constant.

In the case of the fuel-air-ratio runs the chemically correct value was first used and then the mixture was made progressively leaner until a value was reached at which no explosions were obtained. The rich mixtures were then explored, starting from near the chemically correct value and proceeding upward. The upper limit on fuel-air ratio was taken arbitrarily as 0.17 even when explosions could be obtained beyond this point, because the results in this range were not of immediate interest. A constant compression ratio of 11.7 was used.

A similar procedure was followed in the case of the compression-ratio runs. The compression ratio was first set at 11.7 and then decreased by suitable decrements to a value of 8.0, or until no explosions were obtained, after which the range from 11.7 to 15 was investigated. The chemically correct fuel-air ratio was used.

The average values of the standard operating conditions used in these tests were:

Initial pressure	atmospheric
Initial temperature, °F	149
Compression time, sec	0.0060
Dew point of air, °F	−49

A homogeneous mixture of fuel and air was prepared in the manner described in reference 1.

It was assumed that the temperature of the mixture, just before compressing, was the same as that of the water in the combustion-cylinder jacket. This assumption should be reasonably good because the mixture was held in the combustion cylinder for about 3 minutes before proceeding with the test. Moreover the mixture was preheated in the mixing tank, the walls of which were at the same temperature as the combustion cylinder, and the jacketed connection between tank and cylinder was also at the same temperature.

Preliminary runs made on isooctane, using an arbitrary dew point for the air of −49° F, yielded good results and so it was decided to adhere to this arbitrary value as standard.

The compression time was maintained uniform by using a constant driving pressure of 500 pounds per square inch and a cushion pressure of 110 pounds per square inch. Small adjustments had to be made in the cushion pressure, however, in order to compensate for the decrease in friction due to wearing of the lead bands on the piston skirt and in order to ensure proper seating of the piston. (For operation of the machine see reference 1.) Approximately one hour was required to make a run.

After a few runs the cylinder head and piston became covered with a thin brown coating, presumably an oxide. No attempt was made to remove this oxide except to wipe the surfaces with a clean linen cloth in order to remove traces of combustion deposits. It would be very difficult to maintain the surfaces chemically clean, especially in the case of the piston, which was not readily accessible, and therefore it was decided to let the oxide persist as perhaps the easiest means of approximating surface consistency. The cylinder walls, however, not being exposed to the explosive reaction, and being subjected to the frequent rubbing action of the piston, remained clean, dry, and shiny.

These two series of runs embraced the greater part of the experimental work, although a few additional runs were made to test the reproducibility of the apparatus. These check runs are described in the section REPRODUCIBILITY OF RESULTS.

DISCUSSION OF RESULTS

Numerical data pertaining to the runs discussed in this section are given in tables 1 to 8.

Isooctane

Fuel-air-ratio runs.- The records for the first series of runs, made on isooctane at variable fuel-air ratio, are shown in figures 1, 2, and 3. These records, and those which follow, have been reduced to approximately half size. At least two runs were made for each fuel-air ratio and the records are arranged in groups with the corresponding value of the mixture strength indicated in the space below. The groups are arranged according to increasing fuel-air ratio and not according to the serial numbers on the records. The fuel-air ratio ranges from 0.030 to 0.17.

It will be noticed that many of these records show erratic variations in pressure during the delay period. (For this report, delay is defined as the time interval in seconds between the end of adiabatic compression and the instant at which peak pressure is attained.) These pressure variations are only apparent, being caused actually by electrical difficulties. They were eliminated when it was discovered that the B-batteries in the strain-gage circuit, which were supposedly new, were rather badly deteriorated.

It was at first decided to reject any records in which electrical interference or improper seating of the piston rendered the results open to question, but at the conclusion of the work it was thought better to publish all records for the following reasons:

(a) Although electrical difficulties might render the significance of pressure changes dubious, the duration of the delay period was in most cases well defined.

(b) The effects produced by erratic piston motion might suggest something of interest to the reader which the authors may have overlooked.

The results of the first two runs (records 71 and 72) made at a fuel-air ratio of 0.030 indicate that no explosions were obtained. The original pressure-time records were about three times as long as the sections shown here, but were trimmed short for convenience in reproducing.

These records are trimmed to different lengths, as are some of the others in this series, but as the work of assembling the records progressed, it was decided to print at least a 10-inch length of each record regardless of the shortness of the delay. For cases in which the delay was too long to be included in a 10-inch length, the print was shortened by removing the midsection and the record was labeled with the actual duration of the delay.

When the fuel-air ratio was raised to 0.040, explosions were obtained. Thus the leanest mixture strength at which isooctane will autoignite under the conditions of these tests lies between 0.030 and 0.040. The adiabatic pressure at the end of compression was 379 pounds per square inch and the adiabatic temperature was 1340° F absolute, computed on the assumption that the adiabatic exponent was 1.32.

The pressure during the delay period for the runs made at a fuel-air ratio of 0.040 increases by approximately 50 percent before the explosion takes place, but the transition to explosive speed is not gradual; the explosion is sudden and produces a sharp discontinuity in the trace. This type of autoignition appears to be characteristic of isooctane at all mixture ratios less than 0.12. The severity of the explosion and the sharpness of the discontinuity are most pronounced at fuel-air ratios between 0.095 and 0.11. It is in this region also that the maximum explosion pressures are obtained.

The pressure-time records are smooth and well rounded in the explosion region for fuel-air ratios greater than 0.13 and discontinuities and post-explosion vibrations are noticeably absent. Also in this rich region there is little or no rise in pressure during the delay period. The breakaway from a straight line occurs only at the beginning of the lower explosion fillet. This indicates that very little heat is generated by the preliminary reactions at these very rich values until the last phase of the process has been approached.

At fuel-air ratios above 0.16, soot of a fine gossamer texture was deposited in the combustion chamber after the explosion.

The irregular wavering of the trace noted on the right-hand side of some of the records was caused by the sound waves emanating from the cushion chamber at the end of the stroke (see reference 1) and although it is very annoying in the case of the longer delays it does not unduly obscure the general nature of the explosion.

The length of the ignition delay varies greatly with the mixture strength. Long delays are obtained at very rich or very lean mixtures, a minimum value of the delay being realized in the region between 0.067 and 0.078. This observation correlates well with actual engine tests where it is noticed that the tendency toward detonation is a maximum in this region and tends to be less at very lean or very rich mixtures (reference 2).

The curve of ignition delay against fuel-air ratio is shown in figure 4, where each plotted point represents the average values of the delays for each group of records. (This practice of averaging measured values before plotting will be used for all other curves in this section unless otherwise indicated.) The shortest value of the delay is about 0.006 second. The longest value was not determined but explosions were obtained at a fuel-air ratio of 0.17 with delays as long as 0.054 second.

In some of the oscillograph records a low-amplitude vibration of very high frequency can be seen on the compression curve just before the end of the piston stroke. This phenomenon is well illustrated in the group taken at a fuel-air ratio of 0.15 (records 91 to 95, fig. 3). It will be noticed that in all these records the phenomenon occurs in the region where the velocity of the piston changes rapidly, just before seating. A possible explanation is that the piston snout is caused to vibrate with respect to the piston skirt when the acceleration of the piston changes sufficiently. Before the end of the stroke the snout is free to vibrate since it is unrestrained axially and this vibration may be transmitted through the cylinder walls to the head. Also, a perusal of all the records shown in this report brings out the same fact – that these compression vibrations are associated with a rapid change in piston acceleration and are most readily observed when the piston seats slowly. When the piston seats rapidly or even severely, they are almost always absent because then the sudden change in acceleration does not take place until the end of the stroke and the compression vibrations are masked by the mechanical vibrations accompanying impact. (See for instance, record 62, fig. 1.)

Compression-ratio runs.– This series of runs was carried out on isooctane at various compression ratios. The records are shown, grouped according to decreasing compression ratio, in figures 5 to 8. The general trend toward increasing delay and "gentler" explosions with decreasing compression ratio is obvious. The curve of ignition delay against compression ratio is given in figure 9. These records provide a clue to the reason why an engine detonates more severely as the compression ratio is increased, provided that detonation is assumed to be autoignition of the last part of the charge to burn.

The records for compression ratios greater than 8.9 are all of the same type (with the exception of record 107, fig. 6) with the explosion occurring violently at the end of the delay. The pressure rises 50 to 100 percent above the compression value during the delay period. Below the value 8.9 the explosion becomes smooth again and vibrations are absent. Maximum pressure occurs at maximum compression ratio, as would be anticipated.

The adiabatic compression pressures computed with the exponent $n = 1.32$ and the corresponding temperature based on an initial value of 149° F, are given in the following table:

Compression ratio	Adiabatic compression pressure (lb/sq in. absolute)	Adiabatic temperature (°F absolute)
14.9	518	1440
13.9	474	1412
13.5	457	1400
12.4	408	1365
11.7	379	1340
11.5	370	1335
10.7	331	1305
10.0	309	1275
9.4	285	1250
8.9	265	1235
8.5	245	1205
8.0	231	1190

These values of compression ratio were used for all variable compression-ratio runs.

100-Octane Gasoline

Fuel-air-ratio runs.- The first run made on 100-octane gasoline at a fuel-air ratio of 0.030 gave evidence of a weak explosion after a rather long delay period (see record 174, fig. 10). Two additional check runs, however, gave no evidence of an explosion. For the conditions of the test, the lower explosion limit on 100-octane gasoline is therefore in the neighborhood of 0.030, about the same as isooctane. Unfortunately, there is considerable electrical interference on these records.

The next group of runs was made at a fuel-air ratio of 0.040 and three rather different types of record were obtained. The first record (record 171) shows a rather peculiar vibration of very high frequency on the pre-explosion fillet, although the pressure rise is gentle and there are no post-explosion vibrations. The next record of this group (record 172) portrays a more abrupt explosion. The pre-explosion vibrations are absent and the post-explosion vibrations are more pronounced. The third record (record 173) shows a very considerable rise in pressure during the delay period which then gives way to an abrupt explosion followed by heavy vibrations. The delay is roughly the same in each case.

The pre-explosion vibrations shown in record 171 appeared on various occasions throughout the work and it was noticed that as a rule they were associated with a very rough seating of the piston. In record 254 (fig. 16) for instance, the piston, after surging upward at the end of the stroke, seated with a violent shock. As the mechanical vibrations decreased in amplitude, the vibrations of higher frequency became very pronounced. Beats may also be noticed. It appears as though the mechanical shock excited vibrations in the gas as well as in the cylinder head, the latter at lower frequency.

The pre-explosion vibrations of record 171 (fig. 10) might possibly represent some augmented molecular activity, independent of shock excitation, associated with the incipient stages of an explosion, inasmuch as the mechanical vibrations completely died out before the pre-explosion vibrations appeared. Another excellent example to support this latter interpretation may be seen in record 302 (fig. 27). Miller (reference 3) has noticed small-amplitude pressure fluctuations immediately preceding the violent pressure fluctuations that are caused by heavy knock in an actual engine.

Lewis and von Elbe (reference 4) and others have also observed similar gas vibrations although under different circumstances of ignition. Lewis and von Elbe have noticed vibrations on the pressure-time curve in the region where the rate of pressure rise becomes steep. Their observations may have no bearing on the present work inasmuch as the explosions with which they were concerned were initiated by spark ignition rather than by adiabatic compression. They believe that the vibrations which they observed are the result of interactions taking place in the flame front. It is possible, however, that these vibrations are set up in the unburned part of the charge as it is rapidly compressed by the spread of the flame front, in which case they may represent the same phenomenon as observed here. Small-amplitude vibrations may also be noticed in records having otherwise smooth pressure rises such as in records 84 to 86 (fig. 2). They give a dotted-line appearance to the trace in the explosion region.

The group of runs at a fuel-air ratio of 0.078 (fig. 11) is of interest because of the lack of consistency, not only in the length of the delay period but in the type of explosion and magnitude of peak pressure as well. It is not easy to explain this lack of consistency but further consideration will be given to the matter in the next section.

The next three groups of records at fuel-air ratios of 0.095, 0.10, and 0.11 (fig. 12) are more consistent. The explosions are for the most part intermediate between the abrupt and gentle types. The delay does not appear to vary appreciably in this range of fuel-air ratios.

At higher fuel-air ratios the delay increases and the explosions become smooth and well-filleted (figs. 13 and 14). The reproducibility however is not good.

The curve of ignition delay against fuel-air ratio is shown in figure 15. The points do not define the curve well, but the general trend noted for isooctane may be recognized. The fact that gasoline is a heterogeneous mixture rather than a pure compound may be, in some measure, responsible for the erratic behavior.

Compression-ratio runs.- The records for these runs are fairly consistent (see figs. 16 to 18). The delay increases as the compression ratio decreases in the manner of isooctane. Explosion pressures decrease with decreasing compression ratios, as expected.

The abrupt type of explosion is obtained at compression ratios above 10, but the gentle type prevails at values below 10. In the group of runs made at a compression ratio of 8.5, one run failed to yield an explosion and no explosions were obtained in the two runs made at a compression ratio of 8.0.

The minimum ignition pressure and corresponding adiabatic temperature for 100-octane gasoline under the test conditions therefore appear to lie between 231 and 245 pounds per square inch absolute and 1190° and 1205° F absolute, respectively.

The curve of ignition delay against compression ratio is given in figure 19. The curve is well defined.

Triptane

Fuel-air-ratio runs.- The weakest mixture at which explosions were obtained lies between 0.030 and 0.040 (fig. 20).

The explosions are, for the most part, very gentle. Abrupt explosions are obtained at a fuel-air ratio of 0.078, but only after a very considerable rise in pressure during the delay period. Another abrupt explosion is obtained at a fuel-air ratio of 0.11 (record 274, fig. 21), but this appears to be in the nature of an inconsistency.

The delays vary greatly for particular groups and the average values when plotted (see fig. 22) do not outline an easily recognizable trend. These values are indicated in the figure by the small circles. Since only 300 cubic centimeters of triptane were available for these runs, it was not possible to repeat a given run a sufficient number of times to obtain a fair average. The curve was therefore weighted by cross-plotting values of delay from the compression-ratio runs (described in the next section), using values at compression ratios of 11.5 and 11.7 at a fuel-air ratio of 0.066.

The shape of the curve is similar to that of isooctane and 100-octane gasoline.

Compression-ratio runs.- It is difficult to recognize any trend in the variation of the delay period from an observation of the records shown in figure 23. In this figure the compression ratio varies from 14.9 to 11.5 but the inconsistency of the delay among individual records for the two groups at compression ratios of 14.9 and 11.7 almost completely obscures any related variation.

Two types of explosion record may be recognized, the gentle and the discontinuous types. The discontinuous type has the shortest delay in every group and it will be noticed that the pressure during the delay period rises very appreciably before the explosion.

The records for compression ratios between 10.7 and 8.0 are shown in figure 24. The discontinuous type of record gives way to the smooth type as the compression ratio decreases and the trend toward increasing delay is easily recognized, although the consistency is not very good. No explosion was obtained in run 375, at a compression ratio of 9.4, although two other runs made under the same conditions yielded explosions with only moderately long delays. A similar result was obtained at a compression ratio of 8.9.

Very long delays were obtained at the two lowest values of compression ratio (8.0 and 8.5). These delays were the longest obtained for any of the fuels tested under similar conditions.

In spite of the inconsistencies of the records, the average values of delay against compression ratio give a curve the general shape of which is apparent. (See fig. 25.)

Benzene

Fuel-air-ratio runs.- The significant feature of the benzene records (shown in figs. 26 and 27) is the smoothness of the explosions. Not one abrupt explosion is obtained throughout the entire range of fuel-air ratios (0.030 to 0.13). These extreme values represent the lower and upper limits on autoignition for benzene under the test conditions.

From the slowness of the pressure rise in these reactions, it may be inferred that a compression-ignition engine could be operated on a premixed charge of benzene vapor and air, that is, by inducting the charge into the cylinder in the manner of a spark-ignition engine, without encountering a prohibitively high rate of pressure rise. This possibility may be worth trying.

The lengths of the ignition delay are fairly consistent for given values of fuel-air ratio and the trend toward decreasing delay with increasing fuel-air ratio is uniform up to a fuel-air ratio of 0.090.

Above a fuel-air ratio of 0.090 the delay increases again but the reproducibility is not so good and the trend is not so uniform. One record at a fuel-air ratio of 0.10 and another at a fuel-air ratio of 0.11 show no evidences of combustion although explosions are in evidence in the other records of these groups.

No explosions were obtained at a fuel-air ratio of 0.13. All the other fuels tested ignited at fuel-air ratios well above this value.

The curve of ignition delay against fuel-air ratio is given in figure 28. The curve is not clearly determined for values of fuel-air ratio above 0.08.

Compression-ratio runs.- The records for the compression-ratio runs on benzene are presented in figures 29 and 30. The explosions are characterized by slow pressure rises as in the case of the fuel-air-ratio runs. This is true even at the highest compression ratios showing that the initial compression has little effect on the nature of the explosion curve. The length of the ignition delay varies with the compression ratio in the usual manner, however. The relation between delay and compression ratio is shown in figure 31. Only two out of five runs yielded explosions at a compression ratio of 10.0, and no explosions were obtained at a compression ratio of 9.4, showing that the minimum autoignition pressure and corresponding adiabatic temperature for benzene were between 285 and 309 pounds per square inch absolute and 1250° and 1275° F absolute, respectively, for the test conditions.

Comparison of Fuels

The curves of delay against fuel-air ratio for isooctane, 100-octane gasoline, triptane, and benzene (figs. 4, 15, 22, and 28, respectively) are shown superimposed on a single plot in figure 32. In interpreting these curves it must be remembered that in some instances the curve is not too well defined by the experimental data. This is particularly true in the case of 100-octane gasoline and triptane.

All the curves show the same general shape and exhibit a minimum in the region of the chemically correct fuel-air ratio.

Isooctane shows longer values of delay than 100-octane gasoline at mixtures leaner than 0.085, but above this value the reverse is true. The shape of the explosion record obtained for these two fuels is the same at a given fuel-air ratio. Therefore the crossing of the curves might indicate that isooctane would behave better than 100-octane gasoline in an engine as regards detonation at mixture strengths below 0.085, but that above 0.085 the gasoline would be superior. This conclusion is confirmed by the results of supercharged knock testing on these fuels.

The benzene curve shows that the ignition delay of this fuel is more sensitive to changes in fuel-air ratio than gasoline or isooctane, in the range from 0.04 to 0.12. In addition to the fact that the benzene explosions are always gentle, one other fact shown here which may indicate why benzene is such a good antiknock is the position of the benzene curve relative to that of isooctane or 100-octane gasoline. The benzene curve lies above those of the other two fuels and therefore benzene always has a longer delay at a given fuel-air ratio.

The curve of triptane occupies a superior position in the group. Values of delay for triptane are about twice those for isooctane and 100-octane gasoline in the mixture range from 0.040 to 0.10, and are approximately 15 to 50 percent greater than the values for benzene in the mixture range from 0.04 to 0.12.

If delay were the sole criterion of engine detonation, then it would appear that triptane is by far superior to all the other fuels here considered. But the shape of the pressure-time curve during the delay, and especially in the explosion region, is apparently of the utmost importance and in this respect benzene is by far superior. It will be of interest to compare these two fuels with regard to their detonating tendencies in an engine under various conditions.

The curves of figures 9, 19, 25, and 31 for the compression-ratio runs are shown superimposed in figure 33. These curves can be interpreted more closely than those of the fuel-air-ratio runs because there is less scatter of the points in the original curves. Strangely enough, the curve most clearly defined was that of 100-octane gasoline, although it was the most poorly defined in the case of the fuel-air-ratio runs.

It will be observed that isooctane and 100-octane gasoline behave the same for compression ratios greater than 10, whereas below this value the 100-octane gasoline shows up to advantage with respect to long delays. This may mean that under certain conditions, 100-octane gasoline will perform better in an engine in regard to antiknock behavior at lower values of compression ratio. The values of compression ratio given in the figure would not represent the corresponding values of engine compression ratio, of course, because the values given here represent the compression ratio for the end gas and not for the engine cylinder as a whole. If such a check were made on an actual engine and if the curves of figure 33 were sufficiently precise, any disagreement between the interpretation of the curves and the actual observed performance of the engine could be ascribed to heat transfer, or radiation, from the burned to the unburned part of the charge and thus a means would be at hand for estimating the magnitude of this effect.

The curve for triptane is again superior to isooctane or 100-octane gasoline throughout the entire range, although the difference between it and 100-octane gasoline disappears at the lowest compression ratio used. At high values of compression ratio, triptane is twice as good as these fuels in respect to length of delay. Also the explosion records for triptane at high compression ratios show gradual pressure rises in the explosion region with only small abrupt breaks towards the end (fig. 23), whereas the explosion region for the other two fuels at corresponding compression ratios shows that the ignition takes place with great violence (figs. 5 and 16).

In the case of benzene and triptane, there is a small region below a compression ratio of 10.5 in which benzene has a longer delay than triptane, but for values greater than 10.5 triptane has a longer delay than benzene. A comparison of the explosion records of triptane and benzene (figs. 23, 24, 29, and 30) will show that benzene is always superior to triptane as regards smoothness of the reaction. There are no discontinuities for benzene at any compression ratio, whereas the records for triptane, although smooth on the whole, do exhibit small discontinuities just before maximum pressure is reached. It would seem that the smoothness of the benzene ignition should prevent its ever being recognized as audible detonation in an engine. If this is true benzene would be superior to triptane as regards detonation, throughout the entire range, although it would have a greater tendency to preignite in the average engine in which the compression ratio for the end gas is certainly greater than 10. This tendency should be verified by tests in an actual engine.

Comparison of Results with Those of Earlier Investigations

The results of previous work on autoignition by means of a rapid adiabatic compression (see appendix A of reference 1) cannot be readily compared with the results of the present investigation because different fuels, compression times, initial conditions, and so forth, were used and in the earlier compression machines the combustion cylinders were well lubricated. However, the general trends observed in this paper for the variation in ignition delay with fuel-air ratio and compression ratio may also be noted in the works of Tizard and Pye (reference 5), Aubert and Pignot (reference 6), and Fenning and Cotton (reference 7).

REPRODUCIBILITY OF RESULTS

In the case of a given fuel and a constant set of operating conditions, the pressure-time records in general exhibit three major inconsistencies. These are:

(1) Variations in ignition delay

(2) Variations in the shape of the explosion curve

(3) Variations in maximum pressure

An attempt was made to correlate the variations in ignition delay (defined as the time interval in seconds between the end of adiabatic compression and the instant at which peak pressure is attained) with changes in initial pressure and temperature. The variations in initial pressure were barometric, of the order of a few millimeters, and when plotted against the corresponding delay periods, for otherwise constant conditions, showed no correlation whatsoever. A similar procedure was followed in the case of initial temperature. These values were read to the nearest fifth of a degree, immediately before firing the apparatus. It will be remembered that this temperature was that of the circulating water in the cylinder jacket and was read from a thermometer at the outlet of the circulating pump. (See reference 1.) The variation in this temperature was $\pm 1^{\circ}$ F and undoubtedly the variation in the temperature of the cylinder walls was much less, because of the large mass. In any event, no correlation between delay and the small variations in initial temperature could be established.

Small errors in fuel-air ratio could not possibly account for the inconsistencies in the delay because in many instances in the case of the fuel-air-ratio runs a change in the ratio of 0.01 or 0.02 produced a smaller variation than that observed among individual records at a constant fuel-air ratio. It is known for certain that the errors attendant on the mixing of the fuel and air were no greater than 1 percent. This value represented, for the most part, the error involved in reading the hypodermic syringe which was carefully calibrated before use. The errors involved in determining air pressure and temperature were trivial.

No means was available for detecting any lack of homogeneity in the mixture but under the conditions at which the fuel and air were mixed, that is, in a heated tank with thorough agitation by a fan, it is hard to conceive of the mixture being otherwise.

It was suspected that perhaps nitrogen was leaking from the cushion chamber past the gland seal into the combustion cylinder, thereby more or less diluting the charge from run to run. A test was made to check the efficiency of this seal by subjecting the cushion chamber to the usual operating pressure, about 110 pounds per square inch, and observing whether any nitrogen leaked into the cylinder. This was done by attaching a short length of pipe to a special combustion cylinder head (similar to the regular head but having a threaded hole in the center) and immersing the free end of the pipe in a beaker of water. No bubbles were observed showing that the seal and leak-off groove worked satisfactorily.

Variations in the compression time would be expected to produce corresponding variations in the delay. Values of compression time for the various tests are given in tables 1 to 8. In the case of the fuel-air-ratio runs on isooctane (table 1), for instance, the compression time varied between 0.0054 and 0.0077 second. These extreme values represented cases in which the driving and cushion pressures were improperly adjusted. In record 62 (fig. 1) the piston seated so abruptly that a mechanical bounce ensued and in record 87 (fig. 3) the slow seating due to excess of cushion pressure is obvious. The compression time was measured from the instant the piston started to move to the instant it seated. The instant of starting was identified on the records by laying a straight edge along the first white line and noting the point at which the line started to slope downward, and the instant of seating was easily identified by the little V-notch created by the impact. The compression time could be measured by this method to within ±2 percent.

In figure 34 values of delay for isooctane are plotted against compression time at a fuel-air ratio of 0.067 and a compression ratio of 11.7. Although there appears to be a general trend indicating increasing delay with increasing compression time, the variation in the delay at constant compression time is greater in most cases than the total change represented by the trend. Some of the points shown here were taken from records 57 to 64 of figure 1, and the rest were taken from records of unpublished preliminary tests.

For careful work, records having very long compression times should be rejected, but inasmuch as the variation in ignition delay was much greater than the variation in compression time it was decided to print all records and average results, except, of course, for cases in which there was an actual upward surge of the piston before seating.

The actual experimental points for the fuel-air-ratio runs are shown in figures 35 to 38. The scatter of the points is least in the case of isooctane and excessive in the case of 100-octane gasoline, triptane, and benzene. The position of the curve for triptane was determined as described in the section DISCUSSION OF RESULTS. Occasionally the mixture failed to explode under conditions which were apparently identical with those for which explosions seemed to be the usual occurrence. Benzene also behaved poorly in this respect.

The actual experimental points for the compression ratio runs are shown in figures 39 to 42. The scatter of the points is, on the whole, less than in the fuel-air-ratio runs with the exception of triptane. Since these tests were made at the chemically correct fuel-air ratio, this comparison would seem to indicate that this value is more conducive to consistent results.

It is known that in certain types of gaseous explosions, humidity plays an important part. Runs were accordingly made to study the effect of humidity on the ignition delay. The dew point of the air was varied from -63° to 60° F. Isooctane was used in these tests. The fuel-air ratio was maintained at the chemically correct value and the compression ratio at 11.7. All other operating conditions were standard. The records are shown in figures 43 and 44 and the numerical data are given in table 9. No decided trend in the magnitude of the delay is observable in these records, although when the average values are plotted they vaguely indicate a tendency toward increasing delay with increasing humidity. (See fig. 45.) The significant fact is that variations among records of a given group are as great as the variations noted for extreme values at either end of the humidity range. As a matter of fact, the consistency of the ignition delay for this series of runs is as good, if not better, than that for individual groups in the preceding runs in which the variation in dew point was held within $\pm 4^{\circ}$ F.

On the assumption, however, that humidity might have more effect at one fuel-air ratio than another, a very humid and rich mixture (dew point, 68° F; fuel-air ratio, 0.16) was tried. All other test conditions were as in the preceding paragraph. The records, displayed in figure 46, are as consistent as the group shown in figure 3, which are for the same fuel and fuel-air ratio but low humidity. It is thus apparent that small variations in the humidity do not materially affect the duration of the ignition delay.

Tests were then conducted to determine the effect of dust particles on ignition delay. It was possible that some dust entered the combustion chamber with the air, even after the air was filtered. Also, microscopic particles of lint may have been left in the cylinder as a result of using a cloth to remove the loose products of combustion. Three different kinds of dust particles were used: cotton lint, iron filings, and lead filings. The fuel used was isooctane, the fuel-air ratio was 0.067 and the compression ratio was 11.7. The records are shown in figure 47 in which figure it may be noted that, with the exception of record 357, the delays are approximately equal. These records can be compared with the group shown in figure 1 for fuel-air ratios of 0.067, where all conditions are the same except that in the latter group great pains were taken to keep the cylinder free from dust. When it is considered that in the "dust runs" liberal quantities of the particles were sprinkled on the cylinder head, it must be concluded that dust was not predominant among the causes leading to inconsistent results. Numerical data on these runs are given in table 10.

It is interesting to note in this connection that Fenning and Cotton (reference 7) concluded that dust particles were one of the principal causes of inconsistent results in their experiments on the ignition of gases by sudden compression.

Runs were made to determine the effect of washing the cylinder surface with various liquids before firing. The records are shown in figure 48. In the first instance, the surface was sprayed with carbon tetrachloride, then allowed to dry and a run was made on isooctane in the usual manner. A second check run was made in the same way. The delays are about the same length as the delays shown in records 63 and 64 (fig. 1) for isooctane under similar conditions without the carbon tetrachloride spray.

The cylinder surfaces were then sprayed with isooctane and two more runs were made in the same manner. The resulting delay periods have about the same average values as those of the group at a fuel-air ratio of 0.067 shown in figure 1.

Finally the cylinder surfaces were sprayed with lubricating oil and two more tests were made using a fresh oil spray each time. The inconsistency of the results is apparent – both as regards ignition delay and shape of the explosion curve. (Record 407 was badly distorted by electrical disturbances causing a zero shift at the end of the stroke, but from this point on the record is reliable.)

CONCLUSIONS

1. Pressure-time records obtained with the M.I.T. rapid compression machine for isooctane, 100-octane gasoline, triptane, and benzene for the fixed conditions;

initial pressure	atmospheric
initial temperature	149° F
dew point of air	-49° F

and for a compression time of about 0.06 second, show that:

(a) All these fuels have a minimum value of delay in the neighborhood of the chemically correct fuel-air ratio.

(b) The curves of ignition delay against compression ratio for the four fuels show the same trend of increasing delay with decreasing compression ratio.

(c) Triptane shows the longest ignition delay of the fuels tested under nearly all conditions.

(d) The ignition delays of benzene, isooctane, and 100-octane gasoline are approximately the same.

(e) Benzene has the most uniform rate of pressure rise during combustion.[1]

2. Within the limits of the experimental precision, the duration of the ignition delay for isooctane is not appreciably affected by iron filings, lead filings, cotton lint, and humidity, but it is considerably affected by lubricating oil on the cylinder walls.

3. The following relations seem highly probable, provided the theory is accepted that detonation in engines is caused by compression-ignition of the end gas:

(a) The detonating, or knocking, tendencies of a fuel depend not only on the length of the compression-ignition delay, but also on the rate of combustion after self-ignition.

(b) The excellent anti-detonating properties of benzene in engines appear to be due to the slowness of the pressure rise during combustion of the end gas, rather than to an exceptionally long delay period. This characteristic of benzene also furnishes an explanation for the frequent occurrence of preignition rather than detonation as the manifold pressure is raised in a supercharged engine.

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[1]The word combustion is here used to indicate any process taking place in the mixture which causes a rise in pressure above that existing in the combustion chamber at the end of compression.

(c) The resistance of triptane to detonation in engines appears to be due to long ignition delay, as well as to a relatively slow pressure rise during combustion of the end gas.

Sloan Laboratories for Aircraft and Automotive Engines
Massachusetts Institute of Technology
Cambridge, Mass., December 29, 1944

REFERENCES

1. Leary, W. A., Taylor, E. S., Taylor, C. F., and Jovellanos, J. U.: A Rapid Compression Machine Suitable for Studying Short Ignition Delays. NACA TN No. 1332, 1948.

2. Taylor, E. S., Leary, W. A., and Diver, J. R.: Effect of Fuel-Air Ratio, Inlet Temperature, and Exhaust Pressure on Detonation. NACA Rep. No. 699, 1939.

3. Miller, Cearcy D.: A Study by High-Speed Photography of Combustion and Knock in a Spark-Ignition Engine. NACA Rep. No. 727, 1941.

4. Lewis, Bernard, and von Elbe, Guenther: Combustion, Flames and Explosions of Gases. The Univ. Press (Cambridge), 1938, pp. 315-319.

5. Tizard, H. T., and Pye, D. R.: Experiments on the Ignition of Gases by Sudden Compression. Phil. Mag., vol. 44, series 6, no. 259, July 1922, pp. 79, 121.

6. Pignot, A.: Étude des phénomènes de combustion des mélanger gazeux par enregistrement des pressions. Chimie et Industrie, Numero Special, Huitieme Congress de Chimie Industriel, Feb. 1929, p. 231.

7. Fenning, R. W., and Cotton, F. T.: Experiments on the Ignition of Gases by Sudden Compression. R. & M. No. 1324, British A.R.C., 1929.

TABLE 1

DATA ON EXPLOSION RECORDS FOR ISOOCTANE AT VARIOUS FUEL-AIR RATIOS

[Film speed, 200 in./sec; compression ratio, 11.7; initial pressure, 14.7 lb/sq in. abs.; final pressure, 379 lb/sq in. abs.; initial temperature, 609° F abs.; final temperature, 1340° F abs.]

Fuel-air ratio	Run	Ignition delay: Length (in.)	Ignition delay: Time (sec)	Ignition delay: Average value (sec)	Compression time (sec)	Remarks
0.030	71	------	------	------	0.0058	No explosion
	72	------	------	------	.0055	No explosion
.040	69	2.46	0.0123	0.0108	.0058	
	70	1.84	.0092		.0059	
.050	67	1.84	.0092	.0092	.0063	
	68	1.82	.0091		.0058	
.060	65	1.88	.0094	.0081	.0066	
	66	1.35	.0068		.0068	
.067	57	1.09	.0055	.0059	.0056	
	60	1.12	.0056		.0054	
	61	1.10	.0055		.0055	
	62	1.01	.0051		.0054	
	63	1.42	.0071		.0061	
	64	1.35	.0080		.0059	
.078	73	1.47	.0074	.0082	.0059	
	74	1.78	.0089		.0057	
.095	75	1.98	.0099	.0101	.0058	
	76	2.44	.0122		.0059	
	77	1.64	.0082		.0064	
.100	78	1.95	.0098	.0097	.0064	
	79	1.92	.0096		.0062	
.110	80	2.28	.0114	.0112	.0063	
	81	2.18	.0109		.0066	
.120	82	2.88	.0144	.0147	.0062	
	83	2.98	.0149		.0061	
.130	84	3.84	.0192	.0183	.0061	
	85	3.72	.0186		.0075	
	86	3.41	.0171		.0061	
.140	87	6.72	.0336	.0278	.0077	
	88	5.42	.0281		.0066	
	89	5.25	.0263		.0074	
	90	4.63	.0232		.0069	
.150	91	8.08	.0404	.0353	.0069	
	92	7.50	.0375		.0076	
	93	7.10	.0355		.0072	
	94	5.90	.0295		.0076	
	95	6.70	.0335		.0072	
.160	96	6.24	.0313	.0478	.0063	
	97	10.42	.0521		.0063	
	98	12.02	.0601		.0068	Soot deposited
.170	99	10.80	.0540	.0540	.0066	

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TABLE 2

DATA ON EXPLOSION RECORDS FOR ISOOCTANE AT VARIOUS COMPRESSION RATIOS

[Film speed, 200 in./sec; fuel-air ratio, 0.067 (chemically correct); initial pressure, 14.7 lb/sq in. abs.; initial temperature, 609° F abs.]

Compression ratio	Run	Compression pressure (lb/sq in.)	Ignition delay Length (in.)	Ignition delay Time (sec)	Ignition delay Average value (sec)	Compression time (sec)	Remarks
	125		----	-----		0.0058	No explosion
	126		8.36	0.0418		.0061	
8.0	127	231	7.34	.0367	0.0342	.0086	
	128		6.48	.0324		.0060	
	129		6.02	.0301			Piston record lost
	130		5.98	.0299		.0068	
	119		4.62	.0231		.0065	
8.9	120	265	3.74	.0187	.0220	.0070	
	121		4.82	.0241		.0065	
	122		6.34	.0317		.0070	
	123		5.60	.0280		.0109	
	124		6.15	.0308		.0060	
	154		7.23	.0362		.0061	
8.5	155	245	5.50	.0275	.0309	.0059	
	156		5.20	.0260		.0060	
	157		8.08	.0404		.0086	
	158					.0059	No explosion
	159		5.36	.0268		.0057	
	116		2.15	.0108		.0061	
	117		2.95	.0148		.0062	
	118		2.84	.0142		.0068	
9.4	150	285	2.50	.0125	.0130	.0064	
	151		2.60	.0130		.0063	
	152		2.96	.0148		.0060	
	111		2.06	.0103		.0060	
	112		2.37	.0119		.0065	
10.0	113	309	2.42	.0121	.0119	.0074	
	114		2.46	.0123		.0073	
	115		2.60	.0130		.0060	
	106		2.99	.0150		.0065	
	107		3.83	.0192		.0068	
	108		2.18	.0109		.0071	
10.7	110	331	3.06	.0153	.0123	.0059	
	147		1.49	.0075		.0065	
	148		1.95	.0098		.0062	
	149		1.53	.0077		.0069	
	101		1.16	.0058		.0074	
	102		1.76	.0088		.0068	
11.5	103	370	1.73	.0087	.0078	.0074	
	104		1.58	.0077		.0066	
	131		1.12	.0056		.0060	
	132		1.08	.0054		.0064	
12.4	133	408	.86	.0043	.0061	.0063	
	134		1.82	.0091		.0056	
	135		1.22	.0061		.0061	
	136		.86	.0043		.0076	
13.5	137	457	.90	.0045	.0047	.0062	
	138		1.05	.0053		.0060	
	139		.90	.0045		.0063	
	140		1.02	.0051		.0067	
13.9	141	474	.76	.0038	.0044	.0073	
	142		.81	.0041		.0063	
	143		.86	.0043		.0060	
	144		.80	.0040		.0062	
14.9	145	518	.93	.0047	.0040	.0060	
	146		.66	.0033		.0064	

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TABLE 3

DATA ON EXPLOSION RECORDS FOR 100-OCTANE GASOLINE AT VARIOUS FUEL-AIR RATIOS

[Film speed, 200 in./sec; compression ratio, 11.7; initial pressure, 14.7 lb/sq in. abs.; final pressure, 379 lb/sq in. abs.; initial temperature, 609° F abs.; final temperature, 1340° F abs.]

Fuel-air ratio	Run	Ignition delay: Length (in.)	Ignition delay: Time (sec)	Ignition delay: Average value (sec)	Compression time (sec)	Remarks
0.030	174	8.10	0.0405		0.0058	
	175	-----	------		.0057	No explosion
	176	-----	------		.0058	Do.
	177	-----	------		.0058	Do.
.040	171	2.63	.0132	0.0111	.0058	
	172	2.04	.0102		.0062	
	173	1.97	.0098		.0063	
.050	166	1.21	.0061	.0058	.0060	
	167	1.29	.0065			Piston record too faint
	168	0.70	.0035		.0075	
	169	1.22	.0061		.0058	
	170	1.36	.0068		.0059	
.060	164	1.14	.0057	.0057	.0064	
	165	1.14	.0057		.0059	
.066	161	1.60	.0080	.0063	.0059	
	162	1.04	.0052		.0067	
	163	1.14	.0057		.0058	
.078	178	1.29	.0064	.0122	.0062	
	179	1.79	.0090		.0061	
	180	2.36	.0118		.0059	
	181	3.03	.0151		.0056	
	182	5.40	.0270		.0058	
	183	3.21	.0161		.0061	
	184	6.01	.0300		.0059	
	185	2.72	.0136		.0060	
	223	1.65	.0083		.0061	
.095	186	3.28	.0164	.0131	.0058	
	187	3.06	.0153		.0060	
	188	1.78	.0089		.0063	
	189	2.65	.0133		.0078	
	190	2.30	.0115		.0061	
.100	191	2.73	.0136	.0125	.0061	
	192	2.25	.0112		.0059	
	193	2.52	.0126		.0060	
.110	194	2.20	.0110	.0113	.0063	
	195	2.65	.0133		.0058	
	196	2.18	.0109		.0062	
	197	1.96	.0098		.0060	
					.0061	
.120	198	3.17	.0158	.0304		
	199	9.01	.0450		.0059	
	200	4.58	.0229		.0056	
	201	10.10	.0505		.0063	
	202	9.94	.0496		.0058	
	203	3.75	.0188		.0061	
.130	204	3.93	.0196	.0179	.0064	
	205	3.36	.0168		.0079	
	206	3.36	.0168		.0064	
	207	3.98	.0199		.0065	
	208	3.24	.0162		.0066	
.140	209	5.10	.0255	.0240	.0063	
	210	3.84	.0192		.0066	
	211	1.83	.0092		.0066	
	212	5.76	.0288		.0066	
	213	5.56	.0278		.0067	
	214	6.74	.0337		.0064	
.150	215	11.12	.0560	.0447	.0062	
	216	7.92	.0396		.0075	
	217	10.00	.0500		.0061	
	218	9.15	.0457		.0060	
.160	219	------	------	.0384	.0059	No explosion
	220	8.60	.0430		.0063	
	221	------	------		.0062	No explosion
	222	6.75	.0337		.0066	

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TABLE 4

DATA ON EXPLOSION RECORDS FOR 100-OCTANE GASOLINE
AT VARIOUS COMPRESSION RATIOS

[Film speed, 200 in./sec; fuel-air ratio, 0.067 (chemically correct); initial pressure, 14.7 lb/sq in. abs.; initial temperature, 609° F abs.]

Compression ratio	Run	Compression pressure (lb/sq in.)	Ignition delay: Length (in.)	Ignition delay: Time (sec)	Ignition delay: Average value (sec)	Compression time (sec)	Remarks
8.0	244	231	-----	------		0.0073	No explosion
	245		-----	------		.0060	No explosion
8.5	240	245	9.65	0.0483	0.0502	.0062	
	241		11.16	.0558		.0068	
	242		-----	------		.0060	No explosion
	243		8.90	.0446		.0066	
8.9	237	265	6.28	.0314	.0319	.0068	
	238		5.50	.0275		.0064	
	239		7.34	.0367		.0064	
9.4	234	285	4.27	.0214	.0208	.0064	
	235		4.64	.0232		.0064	
	236		3.53	.0177		.0067	
10.0	231	309	2.18	.0109	.0125	.0072	
	232		2.58	.0129		.0064	
	233		2.74	.0137		.0066	
10.7	228	331	1.80	.0090	.0880	.0078	
	229		1.58	.0079		.0072	
	230		1.88	.0094		.0063	
11.5	224	370	1.44	.0072	.0072	.0067	
	225		1.60	.0080		.0067	
	226		1.56	.0078		.0087	
	227		1.06	.0053		.0073	
12.4	246	408	1.22	.0061	.0055	.0059	
	247		1.21	.0061		.0059	
	248		.88	.0044		.0058	
13.5	249	457	1.16	.0058	.0051	.0059	
	250		1.30	.0065		.0058	
	251		.97	.0049		.0068	
14.9	252	518	.87	.0044	.0058	.0062	
	253		1.06	.0053		.0059	
	254		1.40	.0070		.0098	
	255		1.27	.0064		.0061	

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TABLE 5

DATA ON EXPLOSION RECORDS FOR TRIPTANE
AT VARIOUS FUEL-AIR RATIOS

[Film speed, 200 in./sec; compression ratio, 11.7; initial pressure, 14.7 lb/sq in. abs.; final pressure, 379 lb/sq in. abs.; initial temperature, 609° F abs.; final temperature, 1340° F abs.]

Fuel-air ratio	Run	Ignition delay: Length (in.)	Ignition delay: Time (sec)	Ignition delay: Average value (sec)	Compression time (sec)	Remarks
0.030	264	-----	------		0.0060	No explosion
	265	-----	------		.0064	Do.
.040	261	2.80	0.0140	0.0270	.0057	
	262	7.20	.0360		.0058	
	263	3.36	.0168		.0060	
	400	8.04	.0402		.0061	
.050	259	4.93	.0246	.0235	.0062	
	260	4.48	.0224		.0059	
.066	256	3.73	.0186	[a].0208	.0059	
	257	----	----		.0062	No explosion
	258	4.59	.0229		.0064	
.078	266	3.30	.0165	.0172	.0064	
	267	3.58	.0179		.0061	
.090	268	3.27	.0154	.0303	.0061	
	269	5.62	.0281		.0062	
	270	11.16	.0580		.0060	
	277	3.92	.0196		.0059	
.100	271	6.92	.0346	.0275	.0064	
	272	4.60	.0230		.0064	
	401	5.96	.0248		.0059	
.110	273	7.36	.0368	.0276	.0062	
	274	3.62	.0181		.0059	
	275	5.56	.0278		.0059	
.120	276	8.68	.0434	.0319	------	No piston record
	403	4.07	.0203		.0060	

[a]The value of delay indicated by △ in fig. 22 for this fuel-air ratio was obtained by averaging and cross-plotting six values of delay from the compression-ratio runs on triptane at c.r. = 11.5 and 11.7.

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TABLE 6

DATA ON EXPLOSION RECORDS FOR TRIPTANE
AT VARIOUS COMPRESSION RATIOS

[Film speed, 200 in./sec; fuel-air ratio, 0.066 (chemically correct); initial pressure, 14.7 lb/sq in. abs.; initial temperature, 609° F abs.]

Compression ratio	Run	Compression pressure (lb/sq in.)	Ignition delay			Compression time (sec)	Remarks
			Length (in.)	Time (sec)	Average value (sec)		
8.0	384 385 386	231	14.45 11.66 13.25	0.0723 .0583 .0662	0.0656	0.0063 .0059 .0059	
8.4	381 382 383	245	7.62 9.12 18.64	.0381 .0456 .0933	.0590	.0059 .0061 .0060	
8.9	378 379 380	265	----- 6.22 4.76	------ .0311 .0238	.0275	.0060 .0062 .0061	No explosion
9.4	375 376 377	285	----- 4.62 5.20	------ .0231 .0260	.0246	.0060 .0060 .0059	No explosion
10.0	373 374	309	3.43 3.52	.0172 .0176	.0174	.0058 .0058	
10.7	370 371 372	331	1.83 3.70 1.38	.0092 .0185 .0069	.0115	.0060 .0062 .0063	
11.5	368 369 399	370	1.86 1.25 2.15	.0093 .0063 .0108	.0088	.0070 .0065 .0063	
11.7	396 397 398	379	5.96 1.63 2.75	.0298 .0082 .0138	[a].0173	.0068 .0064 .0065	
12.4	387 388	409	1.55 2.08	.0078 .0104	.0086	.0063 .0060	
13.5	389 390	457	1.52 1.64	.0076 .0082	.0079	.0061 .0063	
14.9	392 393 394 395	518	2.73 1.23 4.32 1.09	.0136 .0062 .0216 .0055	.0117	.0079 .0062 .0067 .0061	

[a]The average value of the delay plotted in fig. 25 for this group is 0.0187 second which includes two values cross-plotted from the fuel-air-ratio runs on triptane.

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TABLE 7

DATA ON EXPLOSION RECORDS FOR BENZENE
AT VARIOUS FUEL-AIR RATIOS

[Film speed, 200 in./sec; compression ratio, 11.7; initial pressure, 14.7 lb/sq in. abs.; final pressure, 379 lb/sq in. abs.; initial temperature, 609° F abs.; final temperature, 1340° F abs.]

Fuel-air ratio	Run	Ignition delay: Length (in.)	Ignition delay: Time (sec)	Ignition delay: Average value (sec)	Compression time (sec)	Remarks
0.030	289	-----	------		0.0061	No explosion
	290	-----	------		.0067	Do.
.040	286	3.64	0.0182	0.0193	.0059	
	287	4.09	.0204		.0071	
	288	3.84	.0192		.0064	
.050	282	4.63	.0232	.0144	.0069	
	283	2.59	.0130		.0061	
	284	2.10	.0105		.0064	
	285	2.15	.0108		.0061	
.060	280	2.16	.0108	.0108	.0068	
	281	2.16	.0108		.0062	
.076	278	1.71	.0086	.0085	.0062	
	279	1.66	.0083		.0065	
.090	291	1.52	.0076	.0079	.0064	
	292	1.88	.0094		.0059	
	293	1.31	.0066		.0063	
.100	294	3.26	.0163	.0185	.0059	
	296	-----	------		.0060	No explosion
	297	2.87	.0144		.0061	
	306	3.87	.0194		.0058	
	307	4.00	.0200		.0061	
.110	298	3.64	.0182	.0232	.0059	
	299	4.39	.0219		.0061	
	300	2.66	.0133		.0063	
	309	----	------		.0074	No explosion
	310	7.89	.0394		.0076	
	311	13.0	.065		.0069	
.120	301	7.70	.0385	.0224	.0064	
	302	2.78	.0139		.0062	
	303	3.91	.0196		.0058	
	308	3.50	.0175		.0063	
.130	304	-----	------		.0057	No explosion
	305	-----	------		.0056	Do.

TABLE 8

DATA ON EXPLOSION RECORDS FOR BENZENE
AT VARIOUS COMPRESSION RATIOS

[Film speed, 200 in./sec; fuel-air ratio, 0.076 (chemically correct); initial pressure, 14.7 lb/sq in. abs.; initial temperature, 609° F abs.]

Compression ratio	Run	Compression pressure (lb/sq in.)	Ignition delay			Compression time (sec)	Remarks
			Length (in.)	Time (sec)	Average value (sec)		
9.4	322	285	----	------		0.0066	No explosion
	323		----	------		.0060	Do.
	324		----	------		.0063	Do.
10.0	317	309	----	------	0.0240	.0058	No explosion
	318		3.52	0.0176		.0058	
	319		----	------		.0059	No explosion
	320		6.08	.0304		.0063	
	321		----	------		.0068	No explosion
10.7	314	331	3.17	.0158	.0117	.0072	
	315		1.26	.0063		.0069	
	316		2.60	.0130		.0065	
11.5	312	370	2.00	.0100	.0112	.0070	
	313		2.46	.0123		.0066	
12.4	325	408	2.18	.0109	.0089	.0064	
	326		1.58	.0079		.0060	
	332		1.59	.0079		.0061	
13.5	327	457	.90	.0045	.0054	.0071	
	328		1.24	.0062		.0063	
14.9	329	518	1.45	.0072	.0056	.0059	
	330		.76	.0038		.0068	
	331		1.16	.0058		.0061	

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TABLE 9

DATA ON EXPLOSION RECORDS FOR ISOOCTANE-AIR MIXTURES WITH AIR AT VARIOUS DEW POINTS

[Film speed, 200 in./sec; fuel-air ratio, 0.067 (chemically correct); compression ratio, 11.7; initial pressure, 14.7 lb/sq in. abs.; final pressure, 379 lb/sq in. abs.; initial temperature, 609° F abs.; final temperature, 1340° F abs.]

Dew point (°F)	Run	Ignition delay			Compression time (sec)
		Length (in.)	Time (sec)	Average value (sec)	
60	333	1.95	0.0098	0.0096	0.0058
	334	2.69	.0135		.0058
	335	1.38	.0069		.0060
	336	1.78	.0089		.0061
	337	1.82	.0091		.0062
25	344	2.06	.0103	.0098	.0060
	345	1.84	.0092		.0061
-11	340	1.84	.0092	.0085	.0060
	341	1.78	.0089		.0075
	342	1.73	.0087		.0076
	343	1.42	.0071		.0079
-38	338	1.80	.0090	.0103	.0060
	339	2.32	.0116		.0060
-49	350	1.37	.0069	.0069	.0063
	351	1.46	.0073		.0064
	352	1.27	.0064		.0067
-63	346	1.52	.0076	.0084	.0074
	347	1.82	.0091		.0074
	348	1.47	.0074		.0070
	349	1.82	.0091		.0057
68	[a]353	8.80	.0440	.0380	.0069
	[a]354	7.58	.0379		.0059
	[a]355	7.45	.0372		.0060
	[a]356	7.00	.0350		.0072

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[a]Run made at fuel-air ratio of 0.160.

TABLE 10

DATA ON EXPLOSION RECORDS OBTAINED TO DETERMINE EFFECT OF DUST AND CONTAMINANTS ON IGNITION DELAY OF ISOOCTANE

[Film speed, 200 in./sec; compression ratio, 11.7; fuel-air ratio, 0.067 (chemically correct); initial pressure, 14.7 lb/sq in. abs.; final pressure, 379 lb/sq in. abs.; initial temperature, 609° F abs.; final temperature, 1340° F abs. Wet air (atmospheric) used in these tests with a dew point of 67° F]

Kind of dust or method of contamination	Run	Ignition delay			Compression time (sec)	Remarks
		Length (in.)	Time (sec)	Average value (sec)		
Cotton dust	357	2.16	0.0108	0.0091	0.0061	
	358	1.45	.0073		.0063	
Lead filings	359	1.26	.0063	.0059	.0064	
	360	1.08	.0054		.0063	
Iron filings	361	1.18	.0059	.0059	.0062	
	362	1.18	.0059		.0067	
Isooctane spray	363	1.22	.0061	.0064	.0069	
	364	1.34	.0067		.0070	
Carbon tetrachloride spray	365	1.55	.0078	.0078	.0058	
	366	1.56	.0078		.0058	
Lubricating oil coating	407	4.24	.0212	.0130	.0060	Heavy soot
	408	1.16	.0058		.0057	Do.

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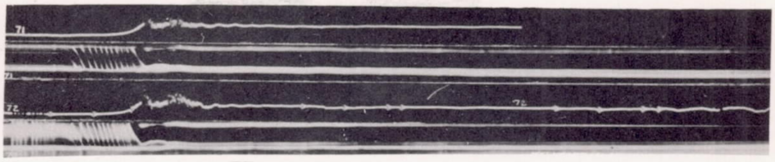
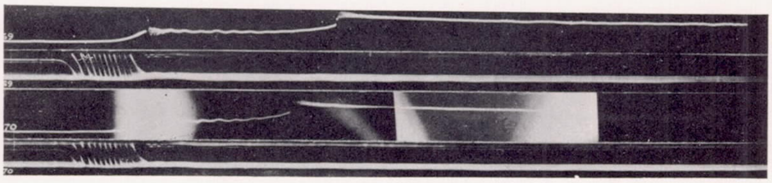
No explosion

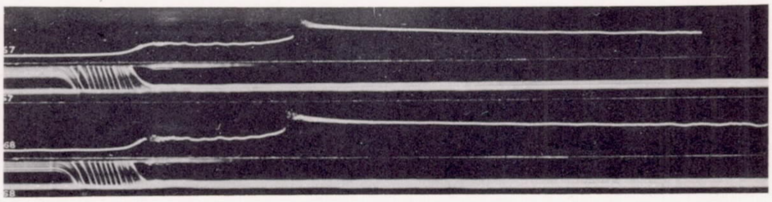
No explosion



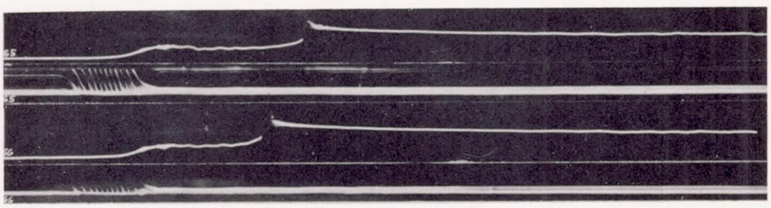
Fuel-air ratio, 0.030



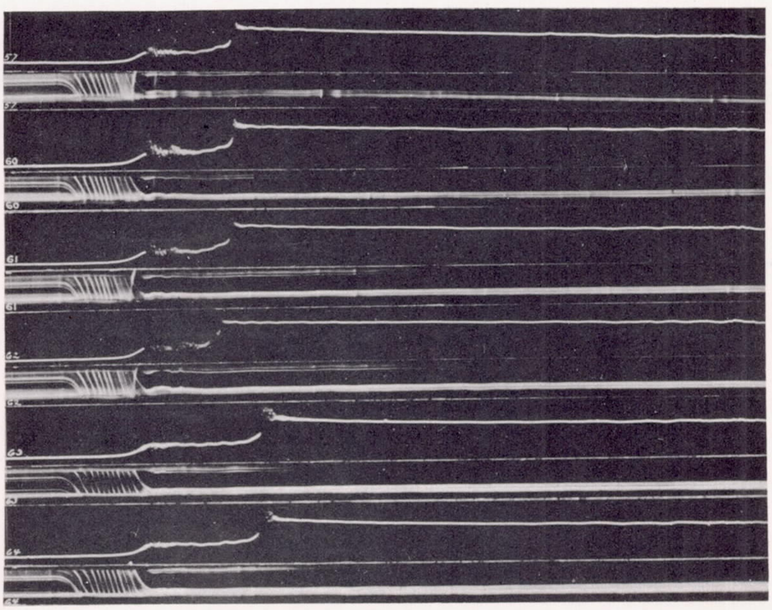
Fuel-air ratio, 0.040



Fuel-air ratio, 0.050



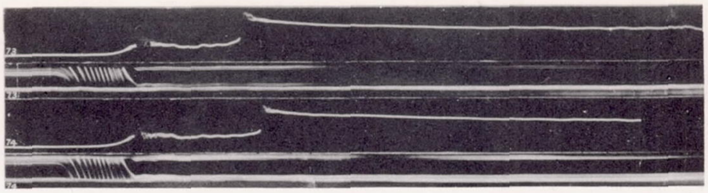
Fuel-air ratio, 0.061



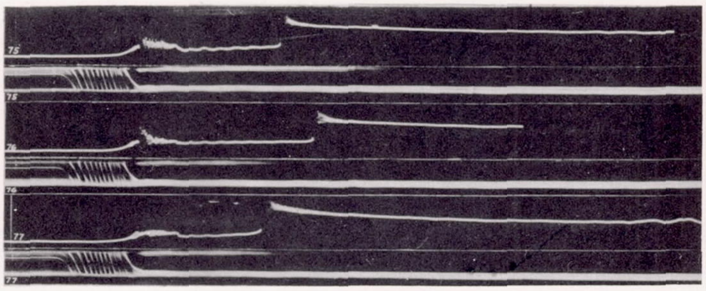
0.005 SEC

Fuel-air ratio, 0.067

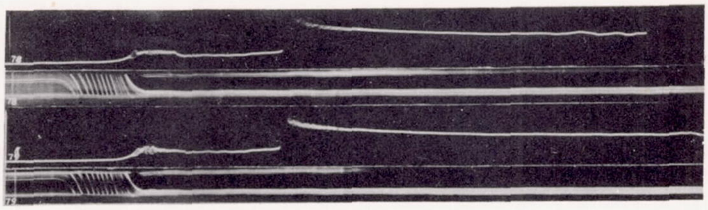
Figure 1.- Explosion records obtained with M.I.T. rapid compression machine for isooctane at various fuel-air ratios.



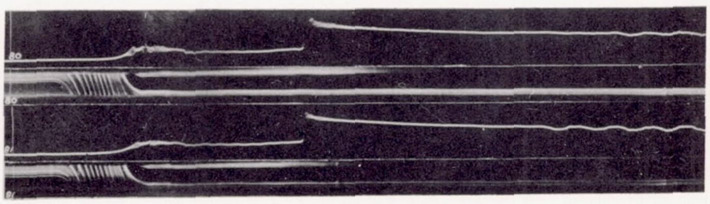
Fuel-air ratio, 0.078



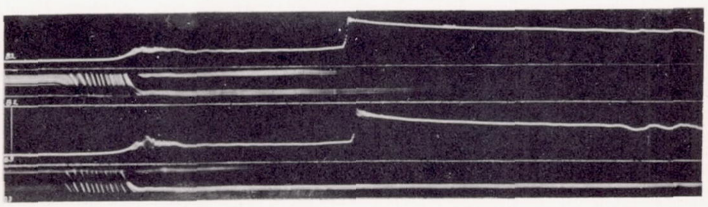
Fuel-air ratio, 0.095



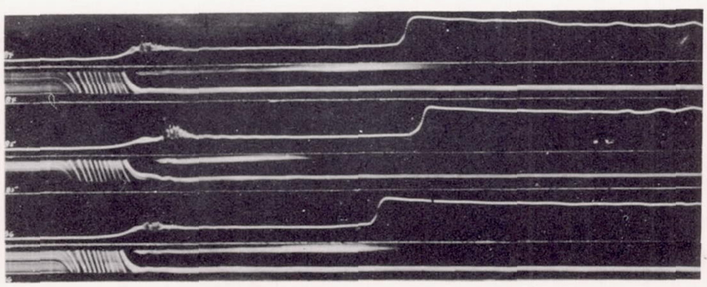
Fuel-air ratio, 0.10



Fuel-air ratio,0.11



Fuel-air ratio, 0.12



0.005 SEC

Fuel-air ratio, 0.13

Figure 2.- Explosion records obtained with M.I.T. rapid compression machine for isooctane at various fuel-air ratios.

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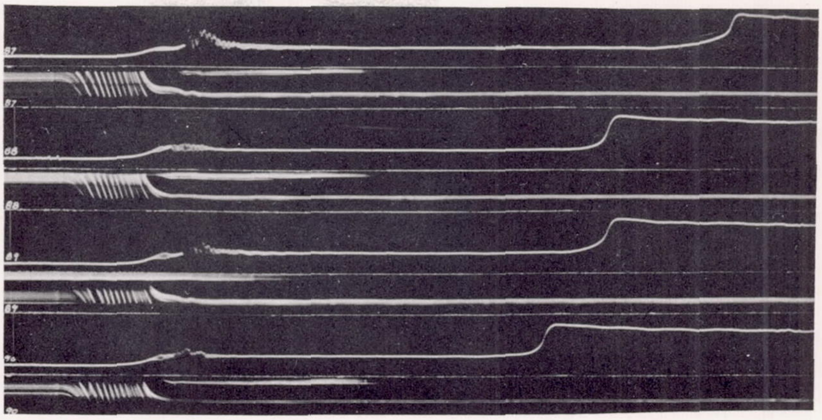
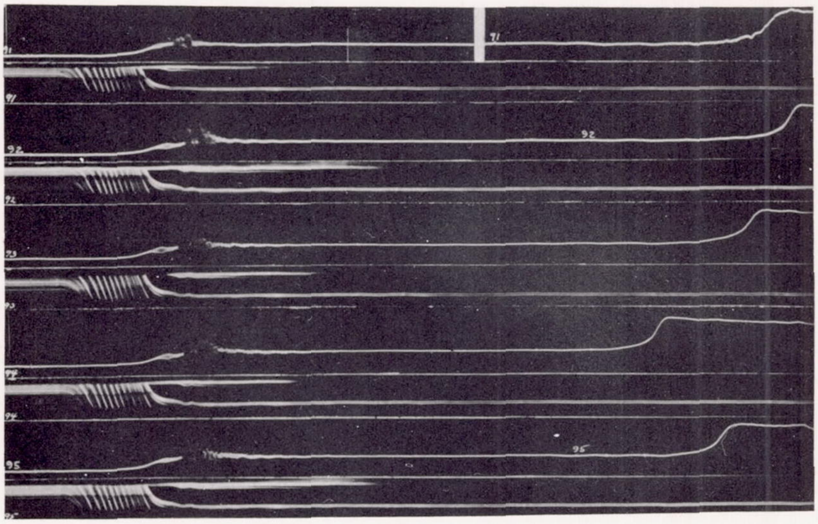


Fuel-air ratio, 0.14

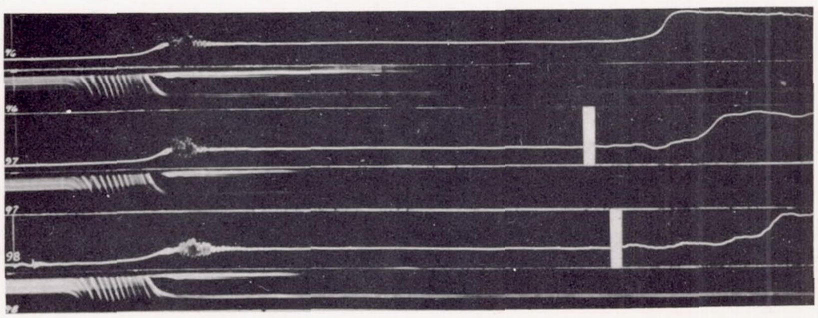
Delay, 0.0404 sec



Fuel-air ratio, 0.15

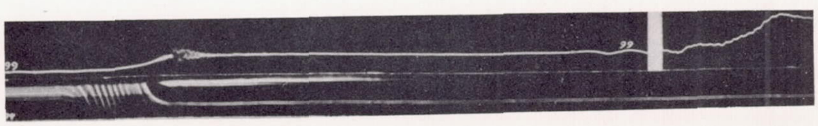
Delay, 0.0521 sec

Delay, 0.0601 sec



Fuel-air ratio, 0.16

Delay, 0.0540 sec



0.005 SEC

Fuel-air ratio, 0.17

Figure 3.- Explosion records obtained with M.I.T. rapid compression machine for isooctane at various fuel-air ratios.

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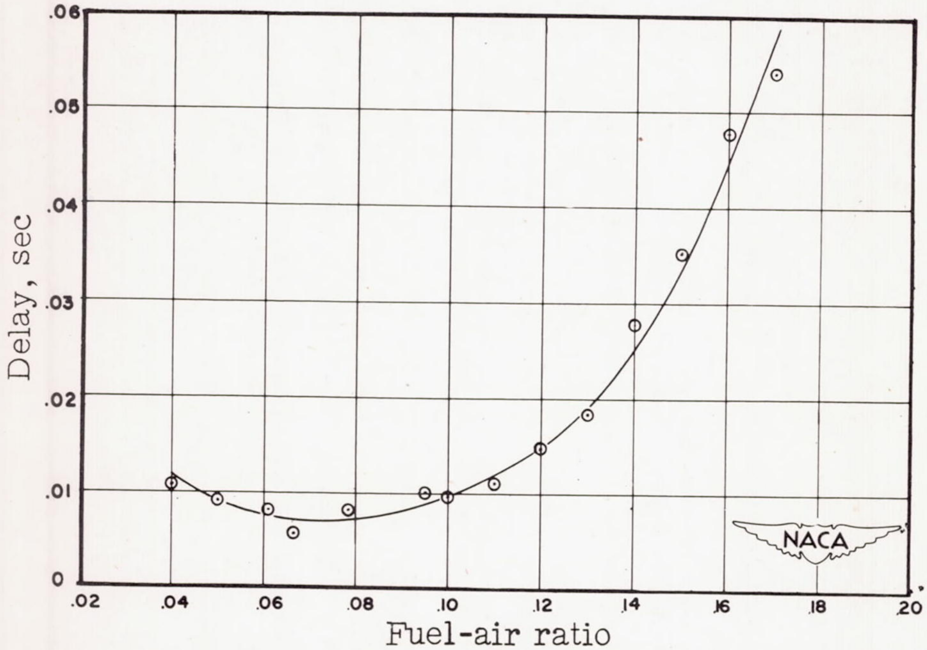
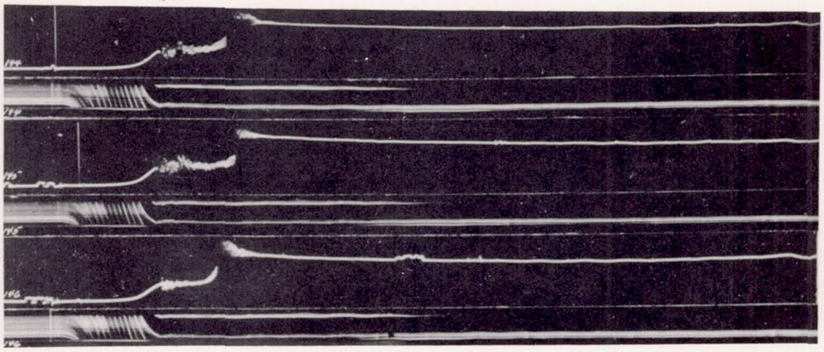
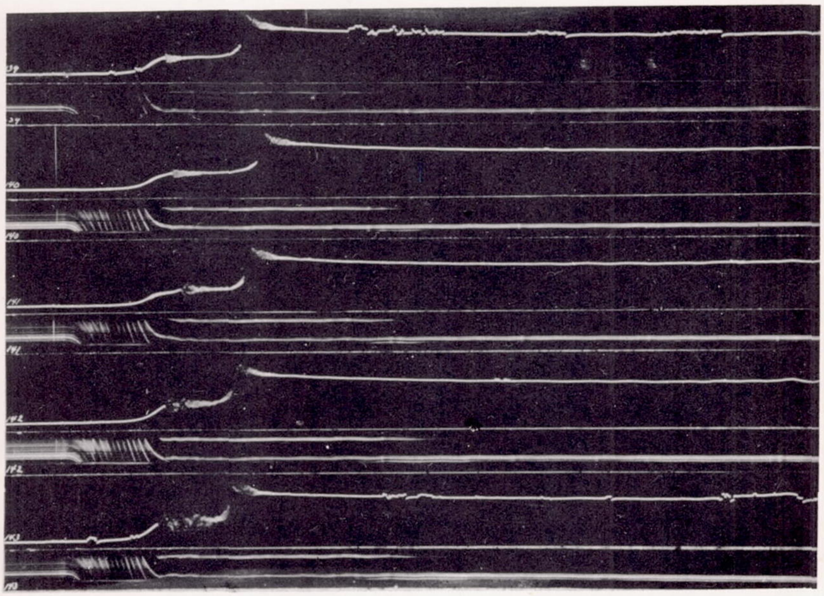


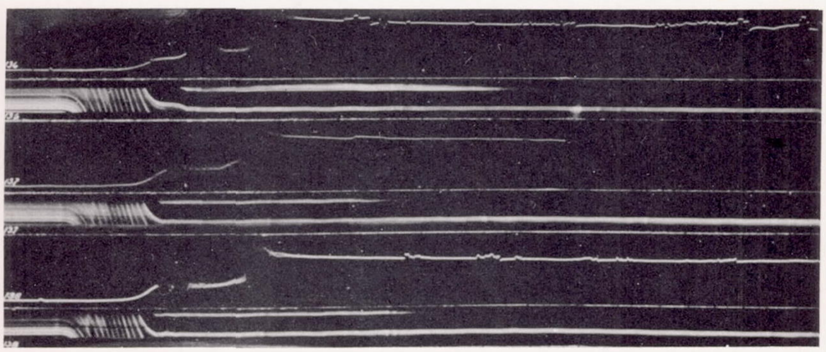
Figure 4.- Effect of fuel-air ratio on ignition delay of isooctane. Plotted points represent average values.



Compression ratio, 14.9



Compression ratio, 13.9



0.005 SEC

Compression ratio, 13.5

Figure 5.- Explosion records obtained with M.I.T. rapid compression machine for isooctane at various compression ratios.

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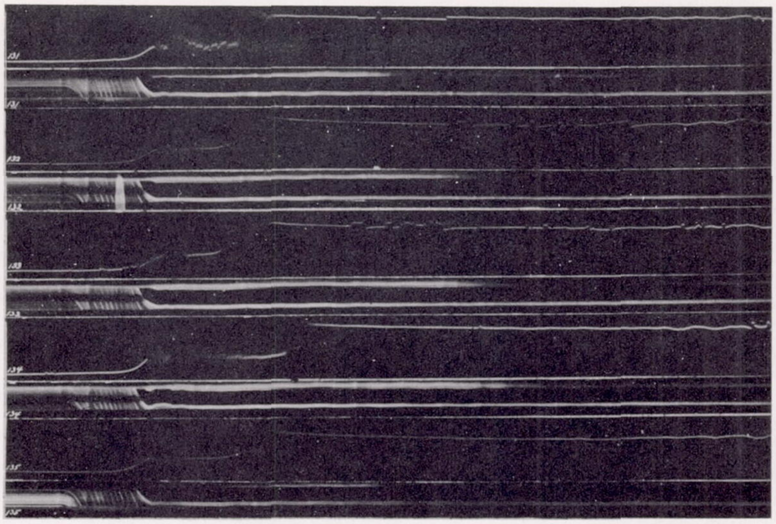
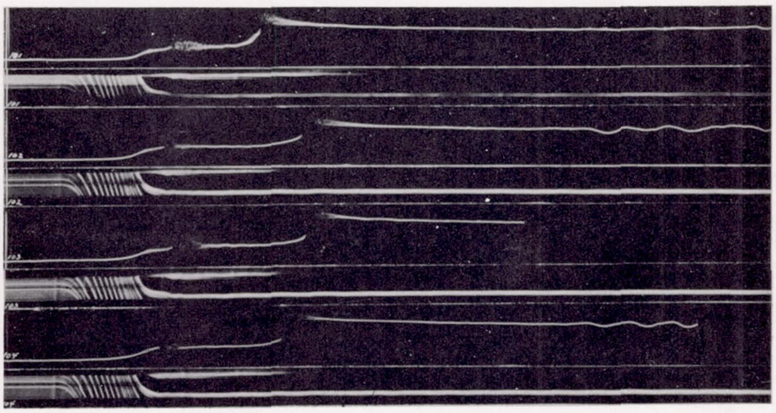
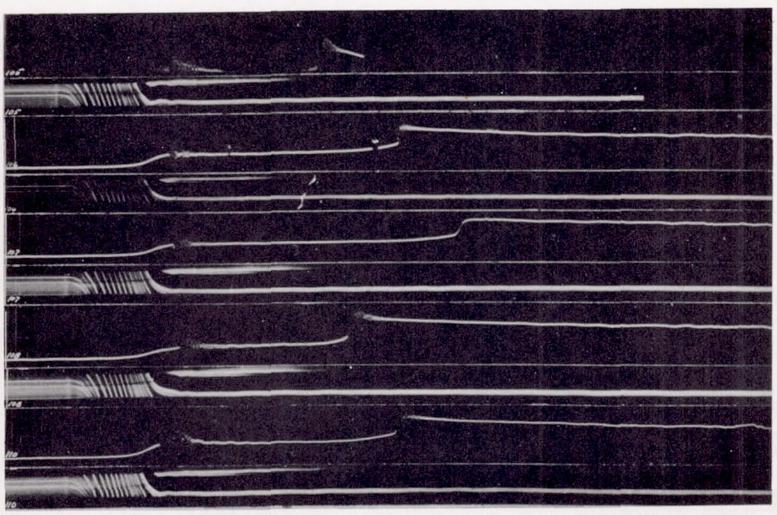


Compression ratio, 12.4



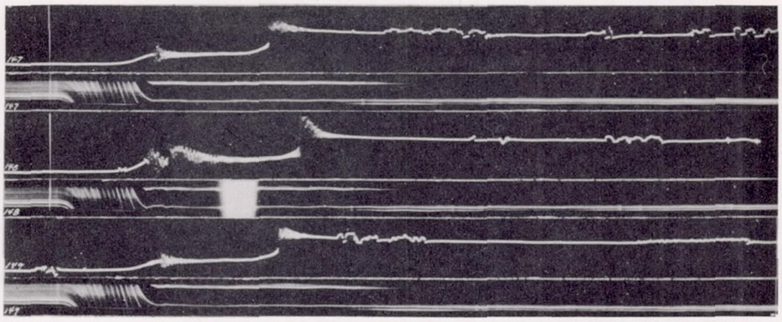
Compression ratio, 11.5



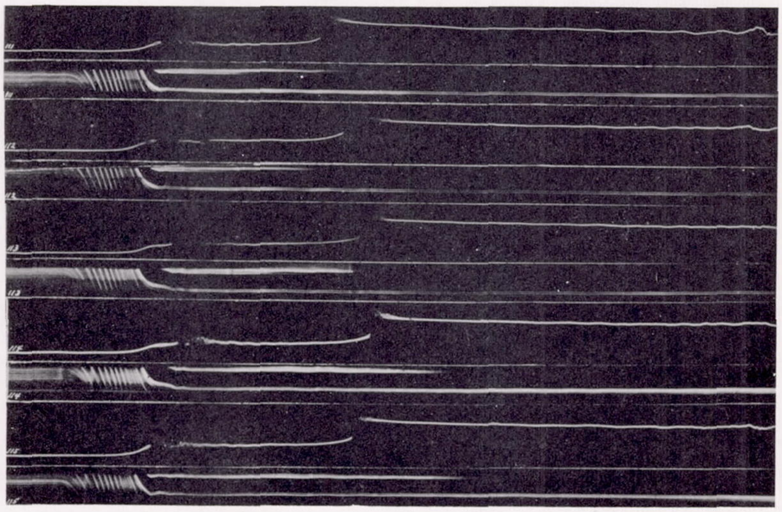
0.005 SEC

Compression ratio, 10.7

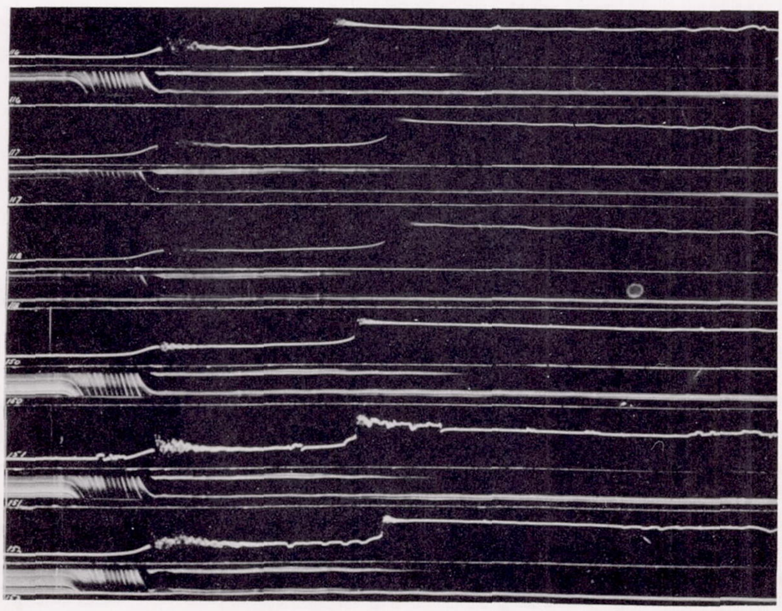
Figure 6.- Explosion records obtained with the M.I.T. rapid compression machine for isooctane at various compression ratios.



Compression ratio, 10.7



Compression ratio, 10.0



0.005 SEC

Compression ratio, 9.4

Figure 7.- Explosion records obtained with M.I.T. rapid compression machine for isooctane at various compression ratios.

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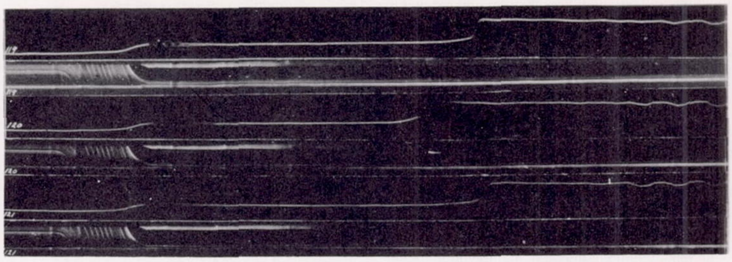
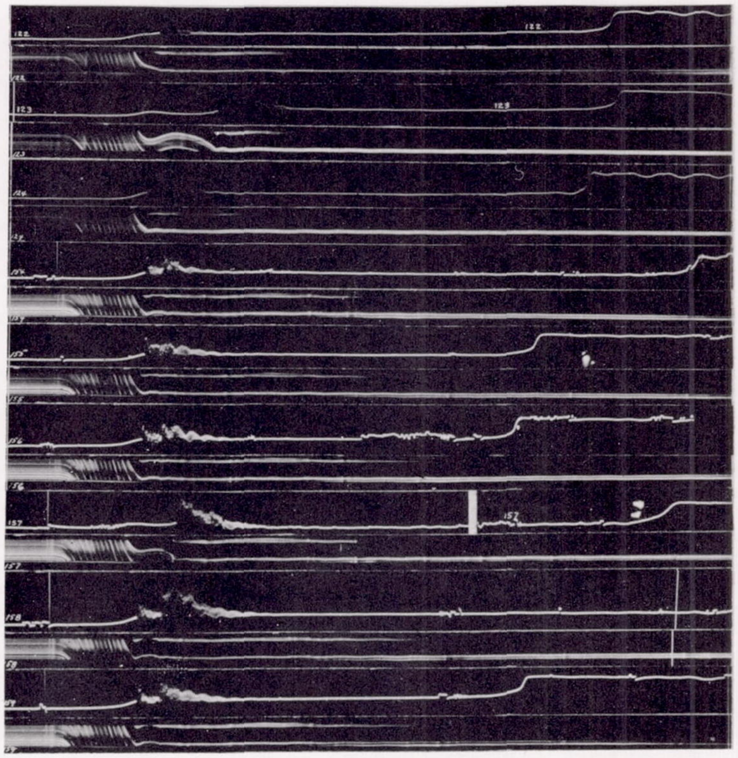


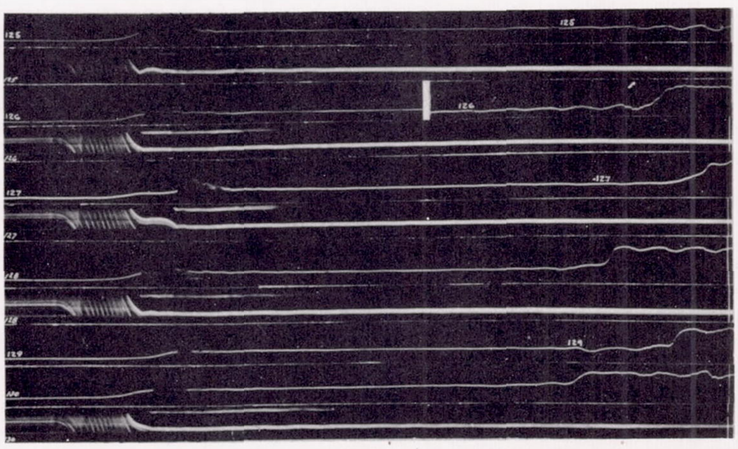
Compression ratio, 8.9



Delay, 0.0404 sec

No explosion

Compression ratio, 8.5



No explosion

Delay, 0.0418 sec

No piston record

0.005 SEC

Compression ratio, 8.0

Figure 8.- Explosion records obtained with the M.I.T. rapid compression machine for isooctane at various compression ratios.

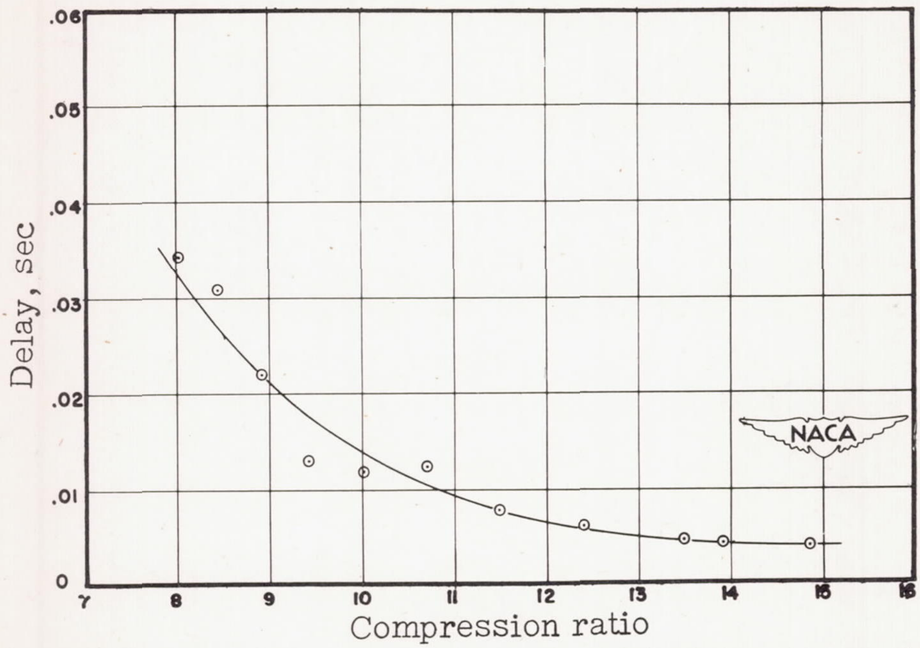
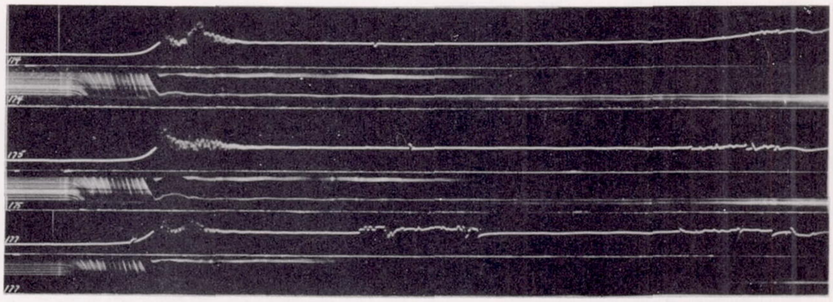


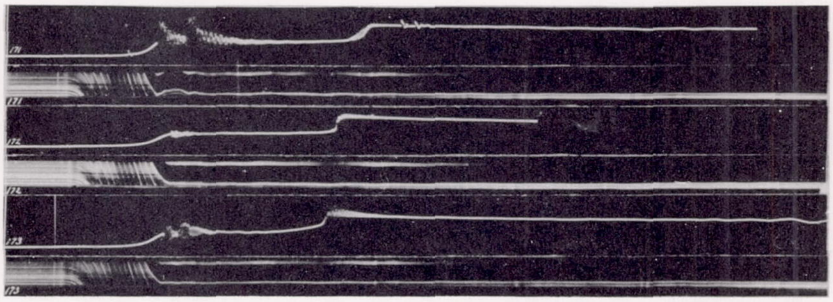
Figure 9.- Effect of compression ratio on ignition delay of isooctane. Plotted points represent average values.

No explosion

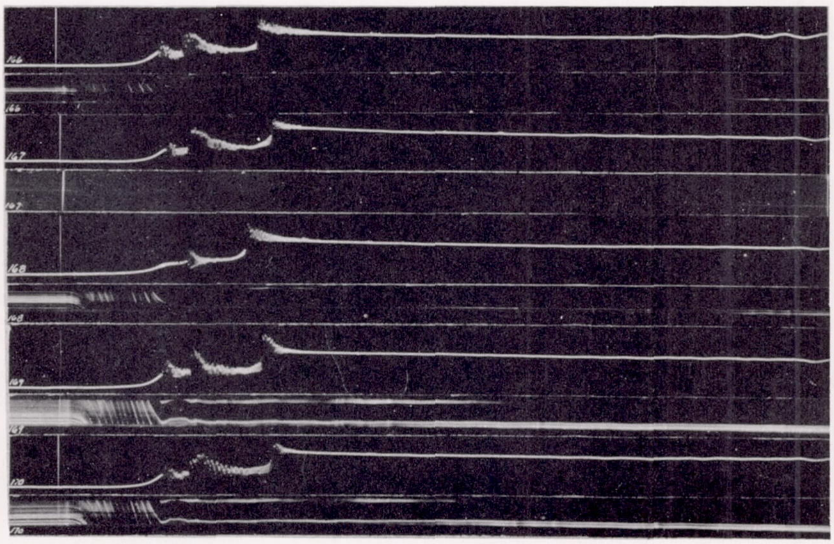
No explosion



Fuel-air ratio, 0.030



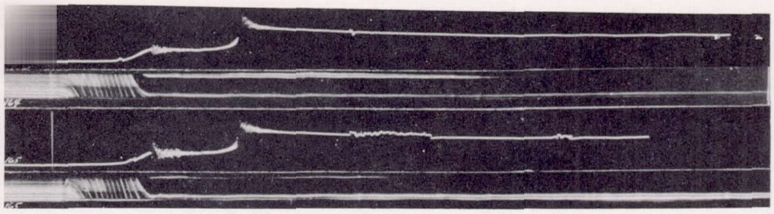
Fuel-air ratio, 0.040



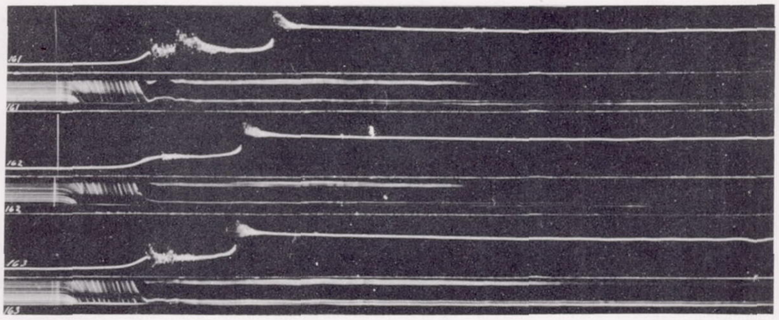
0.005 SEC

Fuel-air ratio, 0.050

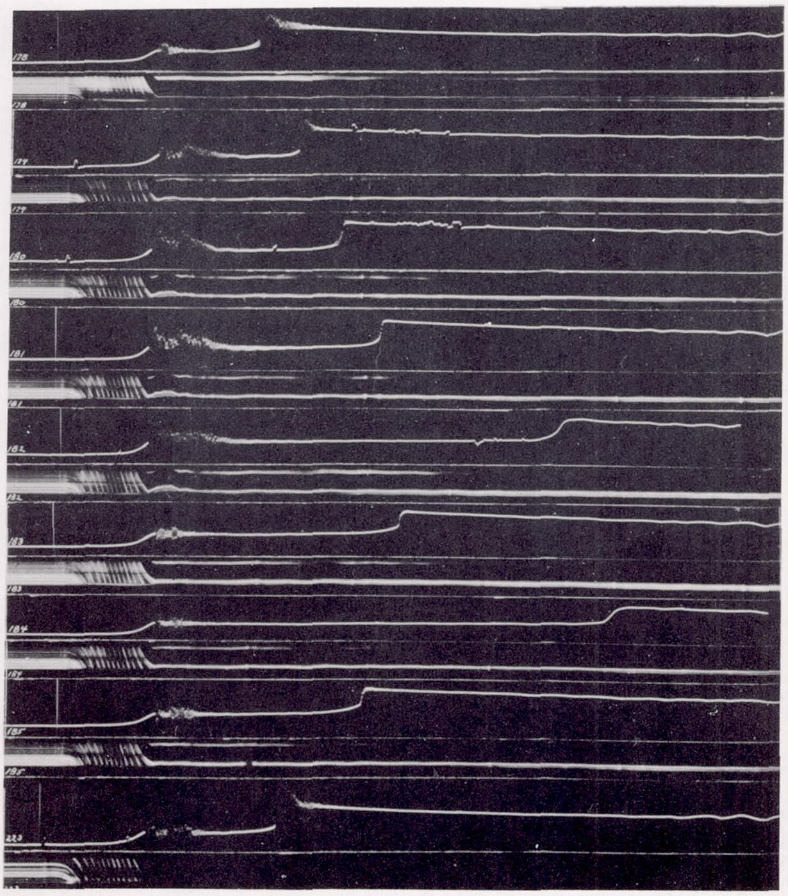
Figure 10.- Explosion records obtained with M.I.T. rapid compression machine for 100-octane gasoline at various fuel-air ratios.



Fuel-air ratio, 0.061



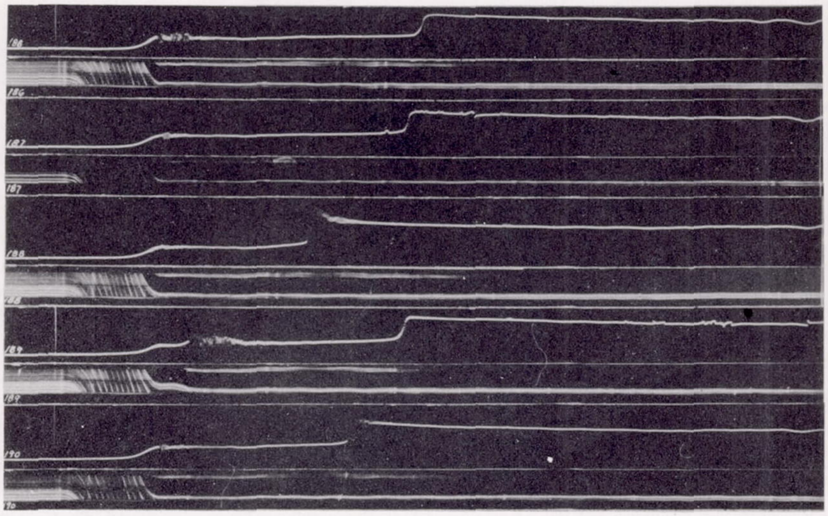
Fuel-air ratio, 0.067



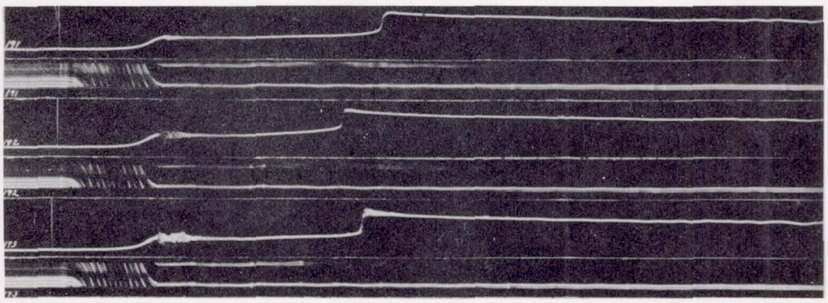
0.005 SEC

Fuel-air ratio, 0.078

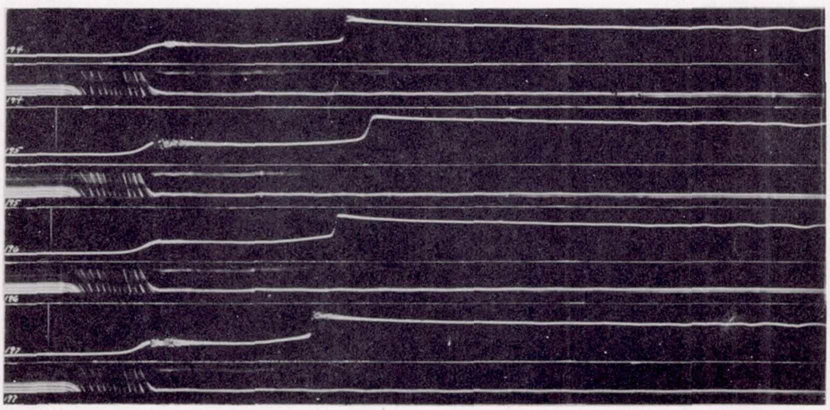
Figure 11.- Explosion records obtained with M.I.T. rapid compression machine for 100-octane gasoline at various fuel-air ratios.



Fuel-air ratio, 0.095



Fuel-air ratio, 0.10



0.005 SEC

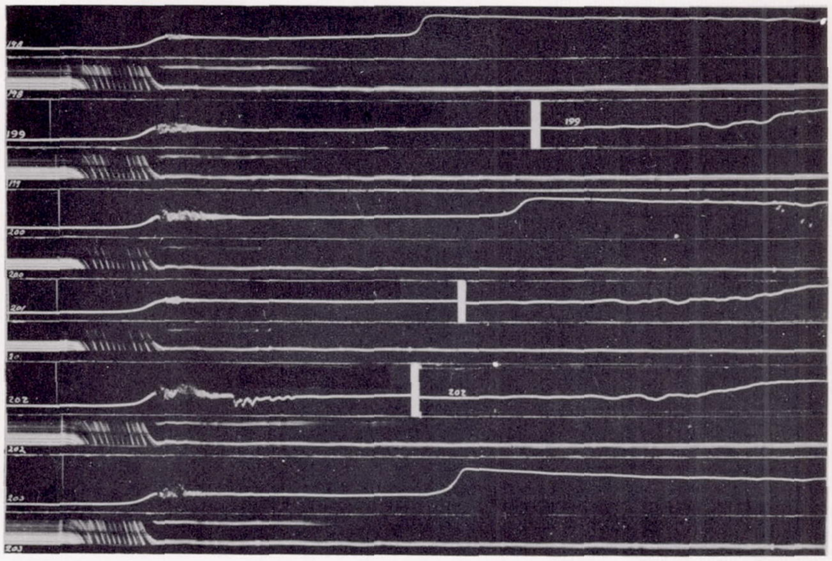
Fuel-air ratio, 0.11

Figure 12.- Explosion records obtained with M.I.T. rapid compression machine for 100-octane gasoline at various fuel-air ratios.

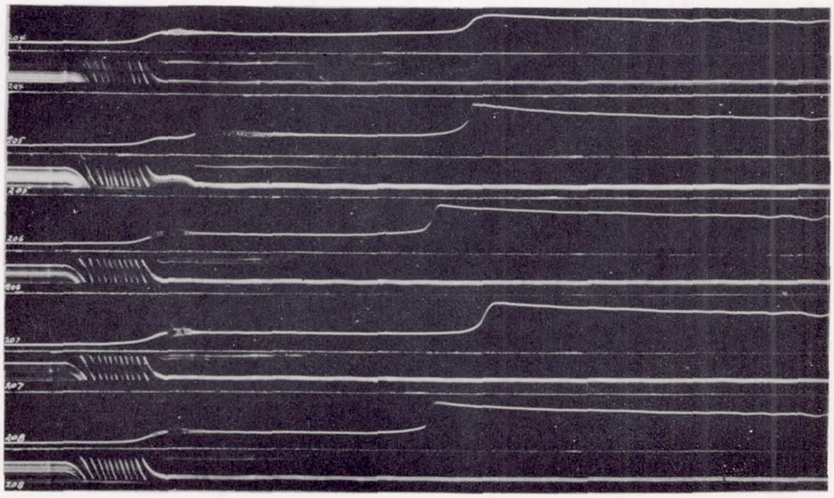
Delay, 0.0450 sec

Delay, 0.0505 sec

Delay, 0.0496 sec



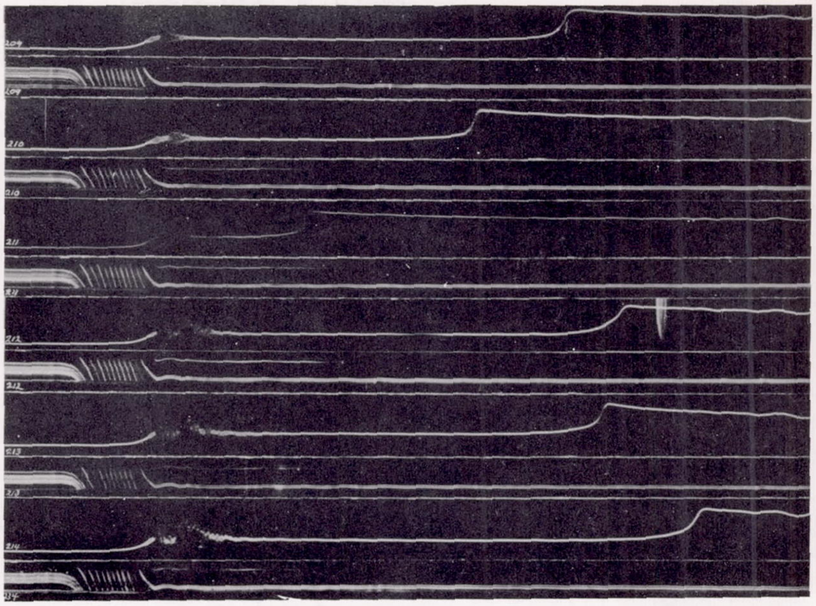
Fuel-air ratio, 0.12



0.005 SEC

Fuel-air ratio, 0.13

Figure 13.- Explosion records obtained with the M.I.T. rapid compression machine for 100-octane gasoline at various fuel-air ratios.

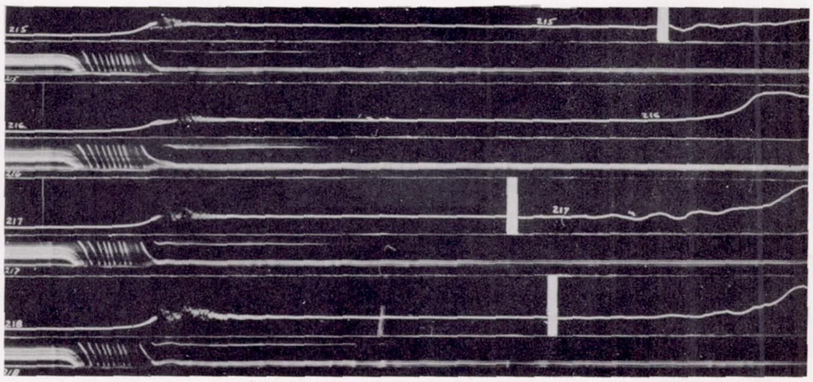


Fuel-air ratio, 0.14

Delay, 0.0556 sec

Delay, 0.0500 sec

Delay, 0.0457 sec

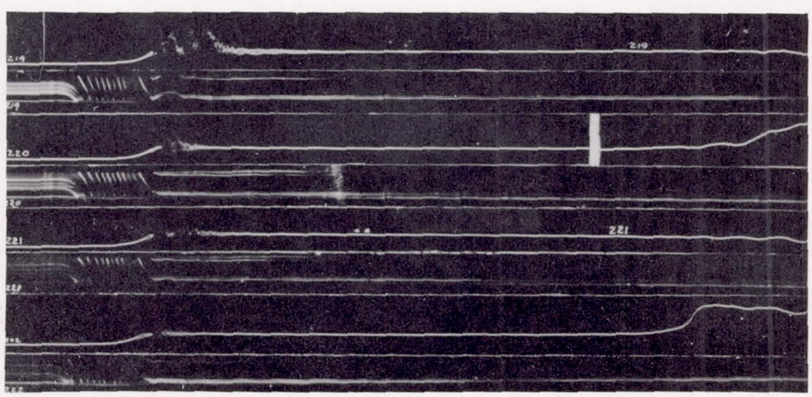


Fuel-air ratio, 0.15

No explosion

Delay, 0.0430 sec

No explosion



0.005 SEC

Fuel-air ratio, 0.16

Figure 14.- Explosion records obtained with M.I.T. rapid compression machine for 100-octane gasoline at various fuel-air ratios.

NACA

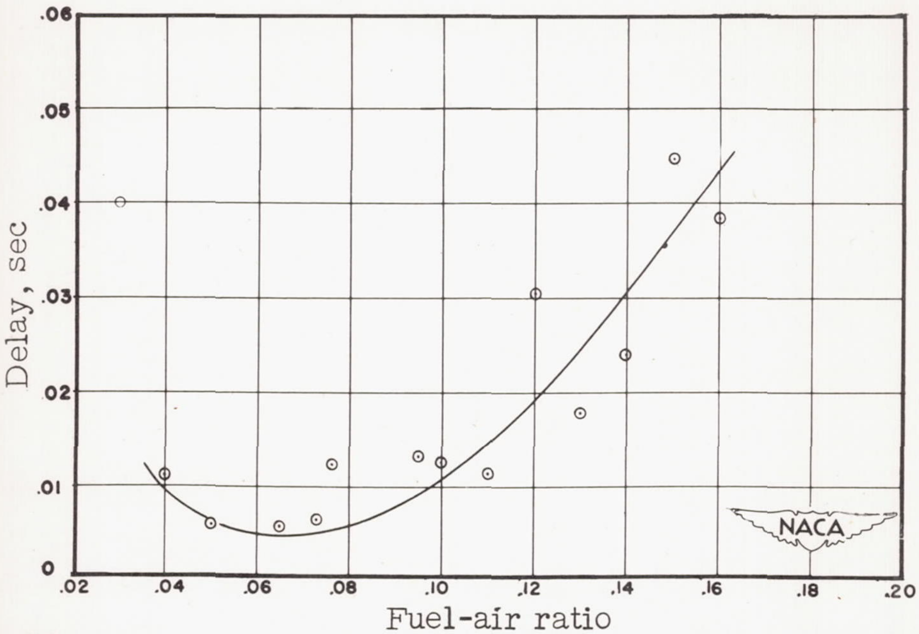
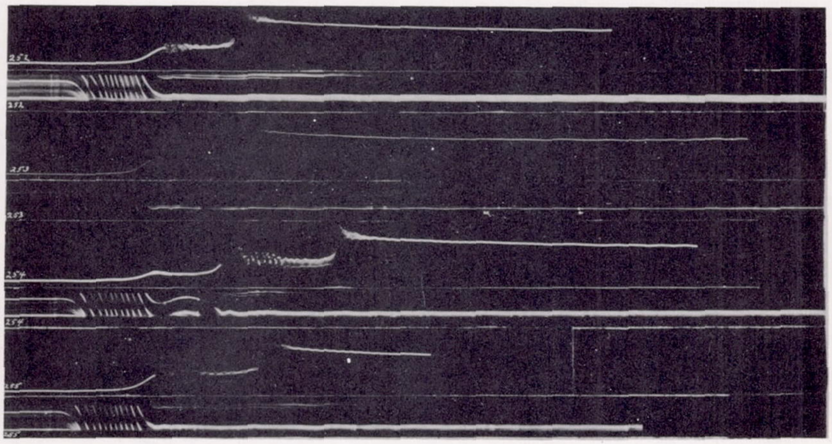
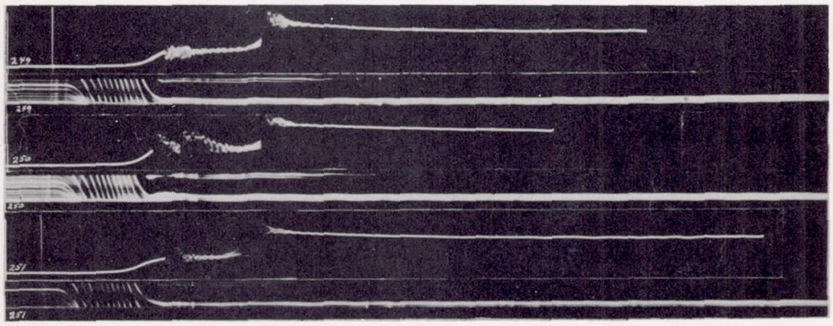


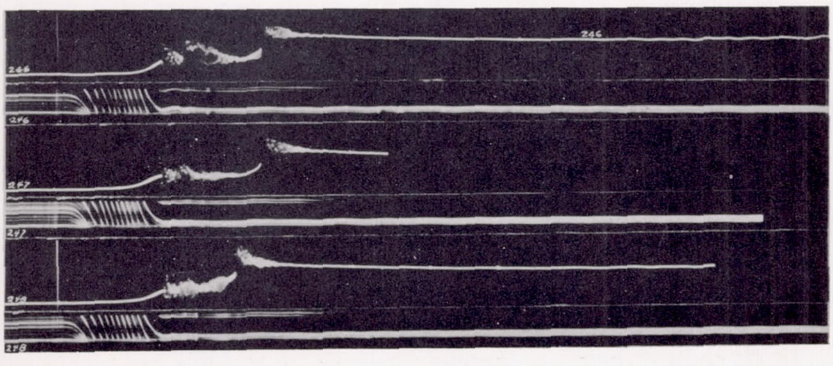
Figure 15.- Effect of fuel-air ratio on ignition delay of 100-octane gasoline. Plotted points represent average values.



Compression ratio, 14.9



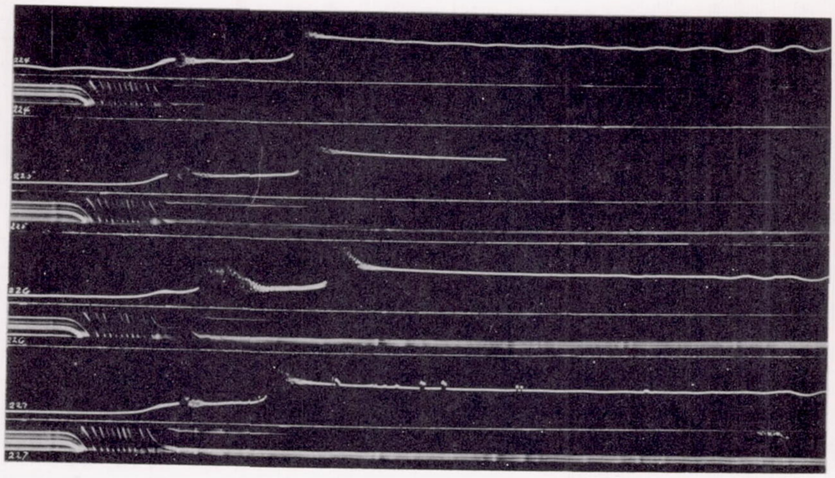
Compression ratio, 13.5



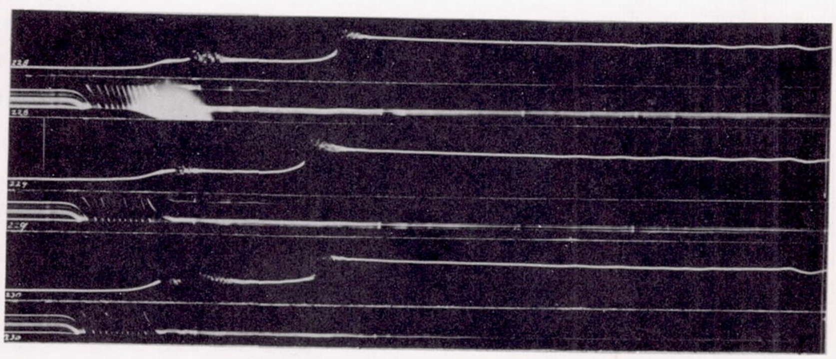
0.005 SEC

Compression ratio, 12.4

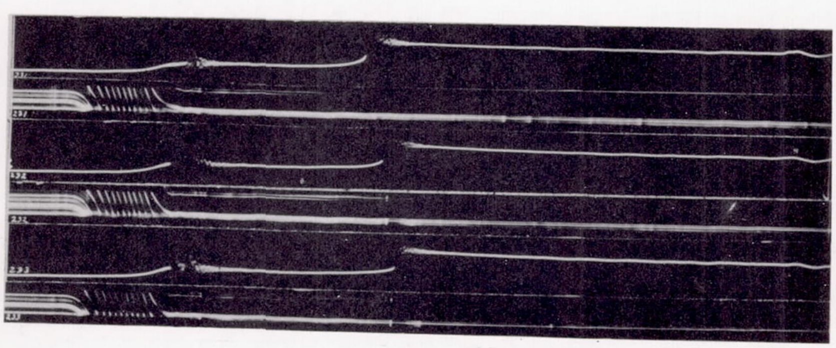
Figure 16.- Explosion records obtained with M.I.T. rapid compression machine for 100-octane gasoline at various compression ratios.



Compression ratio, 11.5



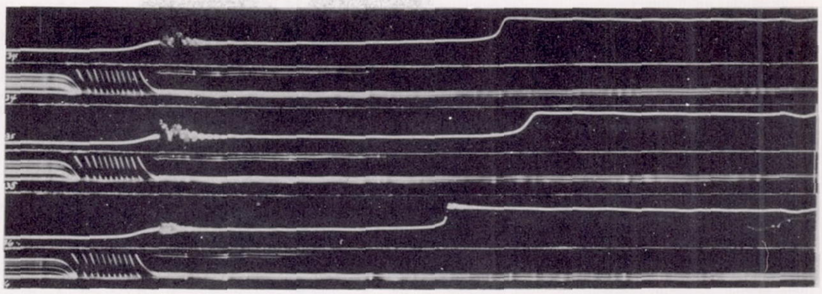
Compression ratio, 10.7



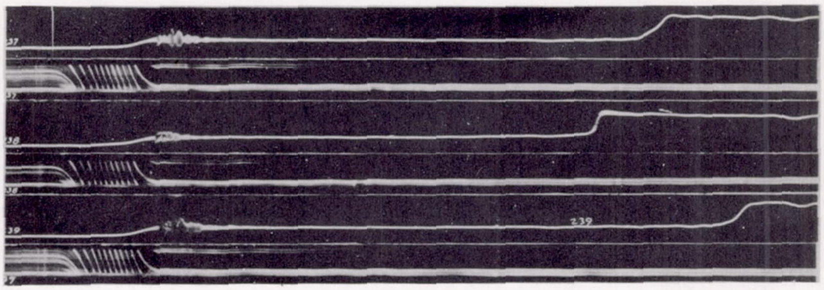
0.005 SEC

Compression ratio, 10.0

Figure 17.- Explosion records obtained with M.I.T. rapid compression machine for 100-octane gasoline at various compression ratios.



Compression ratio, 9.4



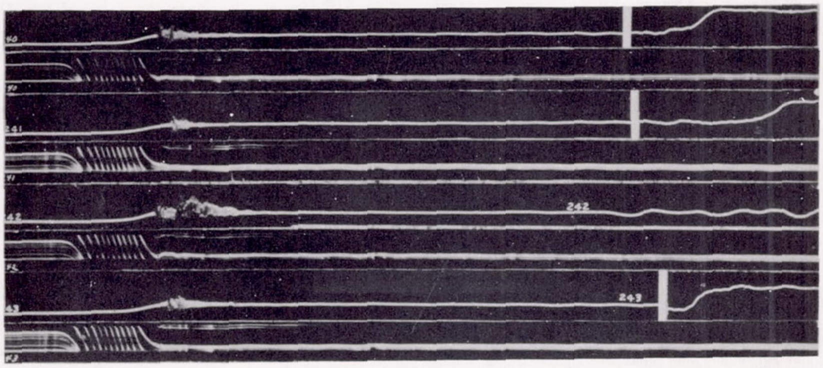
Compression ratio, 8.9

Delay, 0.0483 sec

Delay, 0.0558 sec

No explosion

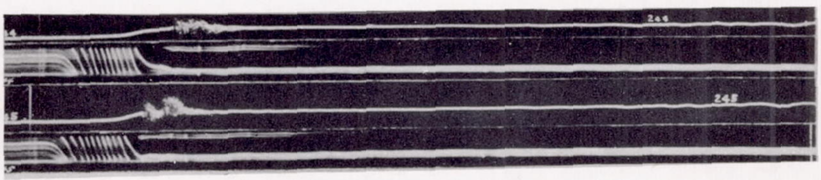
Delay, 0.0446 sec



Compression ratio, 8.5

No explosion

No explosion



0.003 SEC

Compression ratio, 8.0

Figure 18.- Explosion records obtained with M.I.T. rapid compression machine for 100-octane gasoline at various compression ratios.

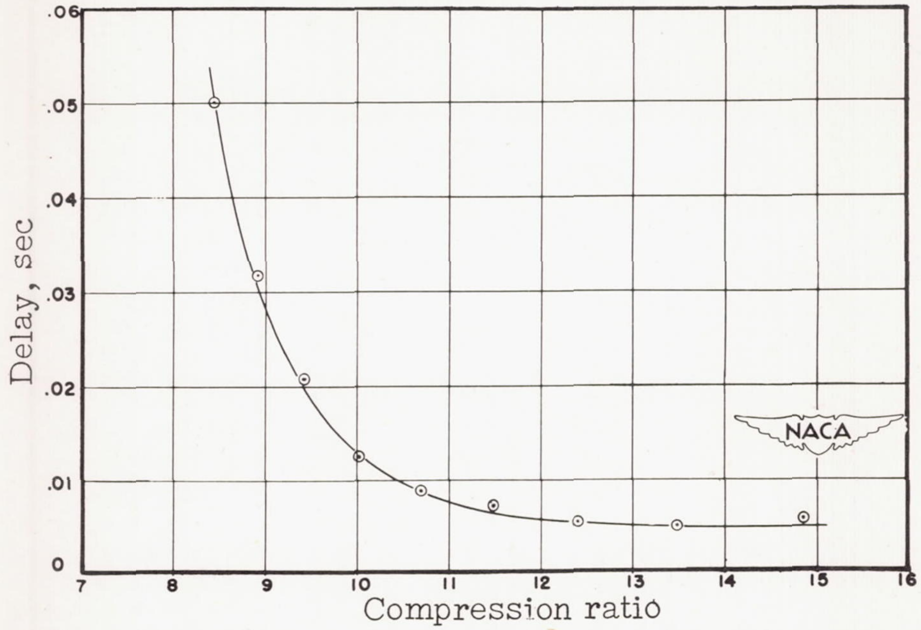
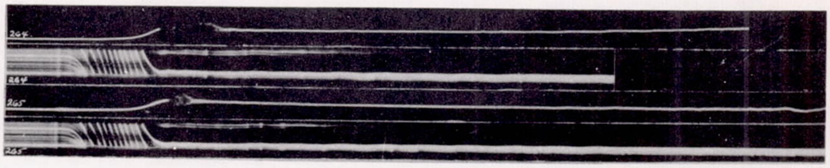


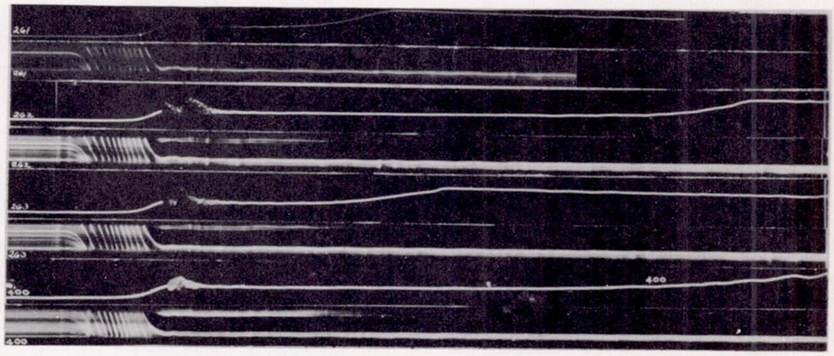
Figure 19.- Effect of compression ratio on ignition delay of 100-octane gasoline. Plotted points represent average values.

No explosion

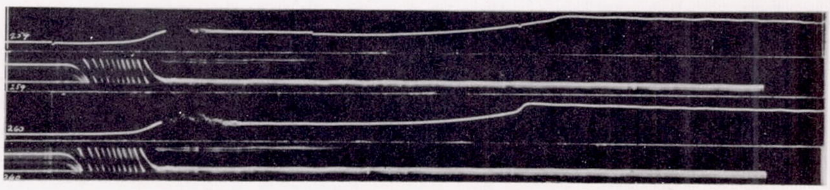
No explosion



Fuel-air ratio, 0.030

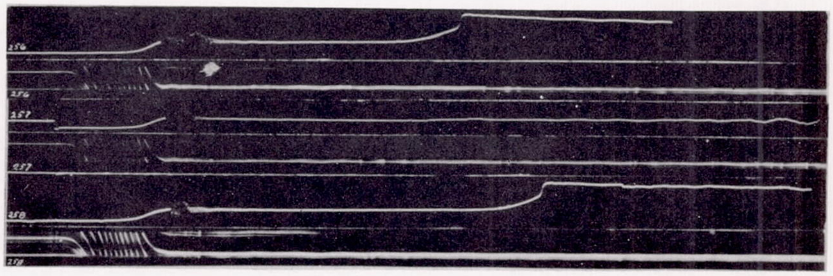


Fuel-air ratio, 0.040

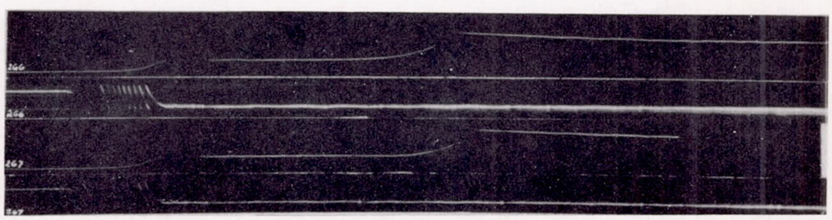


Fuel-air ratio, 0.050

No explosion



Fuel-air ratio, 0.066



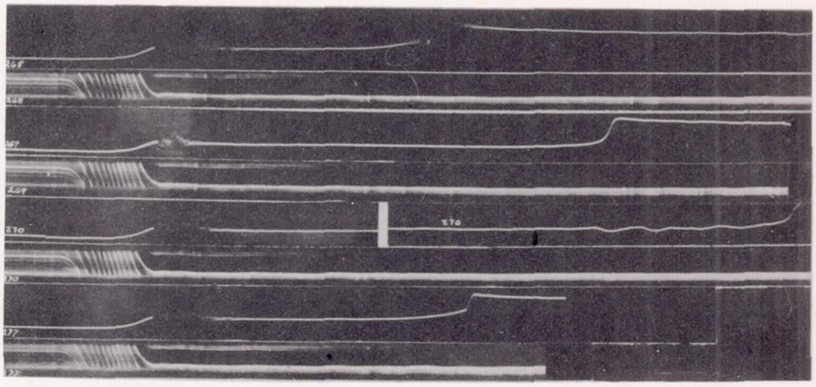
0.005 SEC

Fuel-air ratio, 0.078

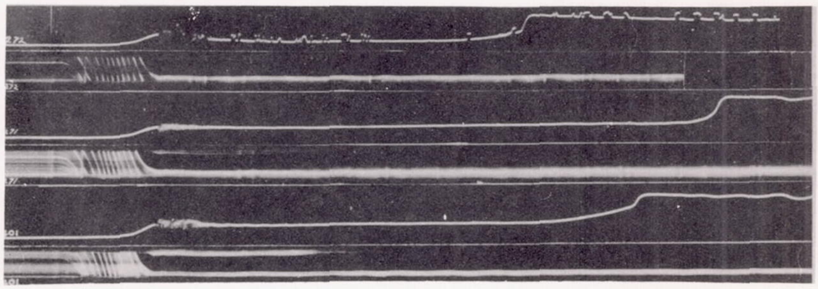
Figure 20.- Explosion records obtained with M.I.T. rapid compression machine for triptane at various fuel-air ratios.

NACA

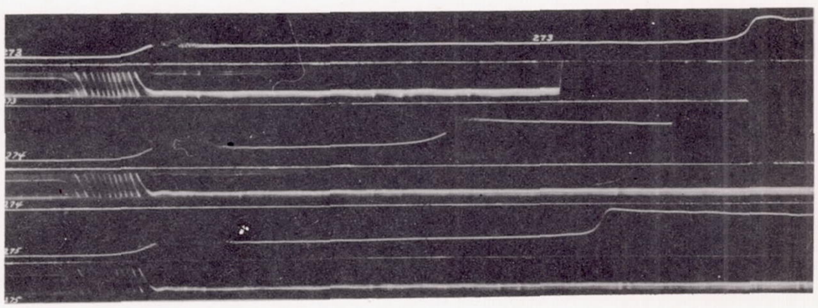
Delay, 0.0558 sec



Fuel-air ratio, 0.090

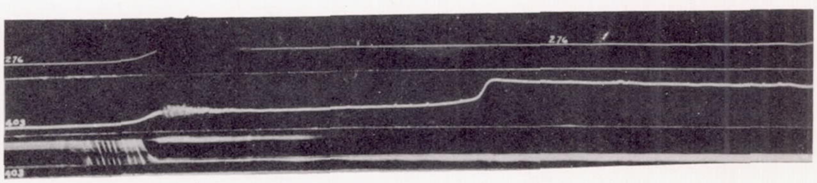


Fuel-air ratio, 0.10



Fuel-air ratio, 0.11

No piston record



0.005 SEC

Fuel-air ratio, 0.12

Figure 21.- Explosion records obtained with the M.I.T. rapid compression machine for triptane at various fuel-air ratios.

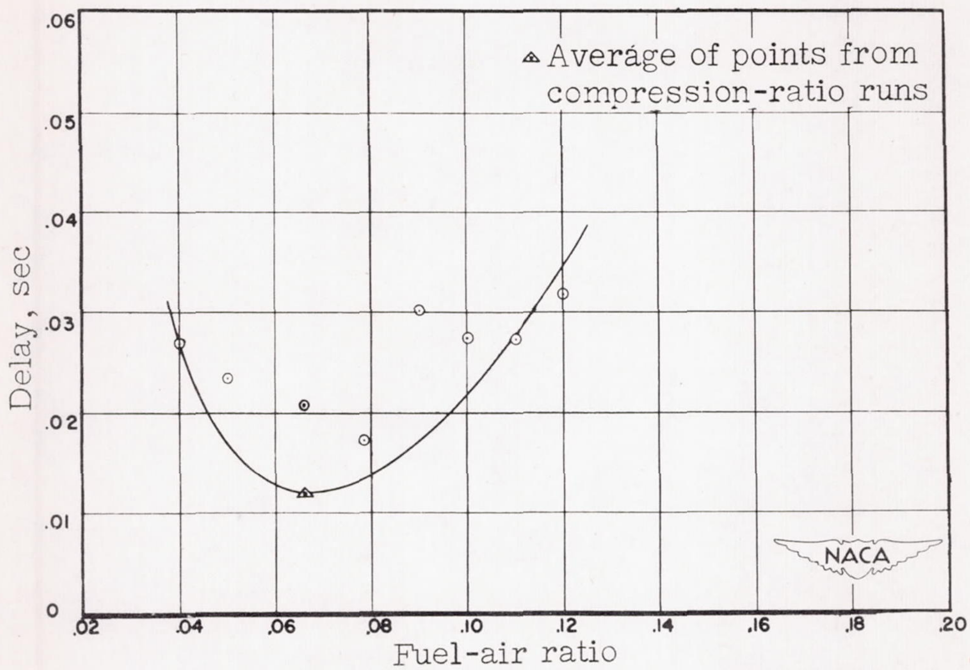
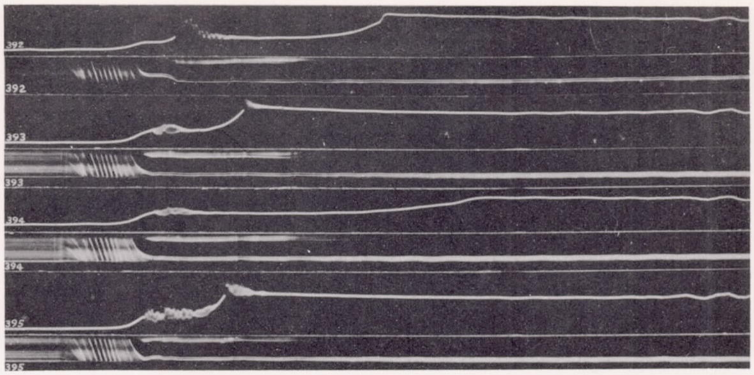
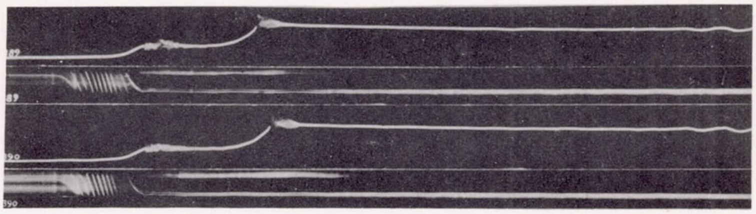


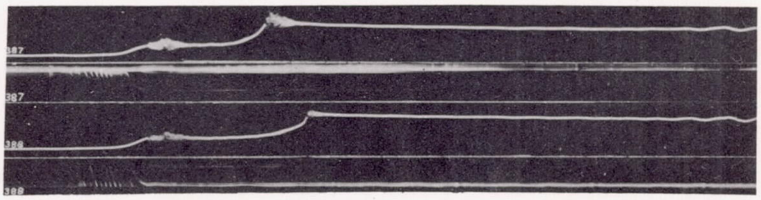
Figure 22.- Effect of fuel-air ratio on ignition delay of triptane. Plotted points represent average values.



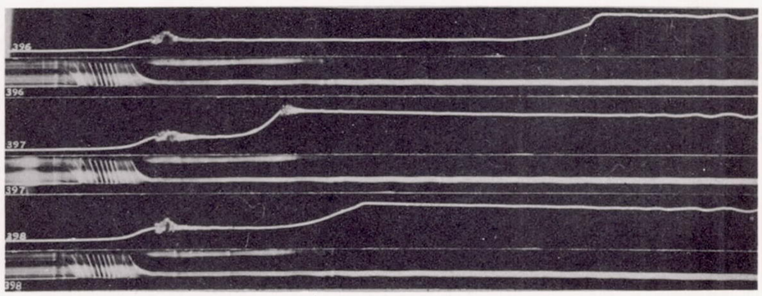
Compression ratio, 14.9



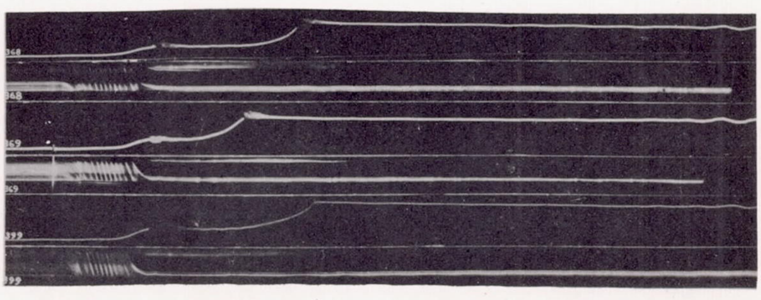
Compression ratio, 13.5



Compression ratio, 12.4



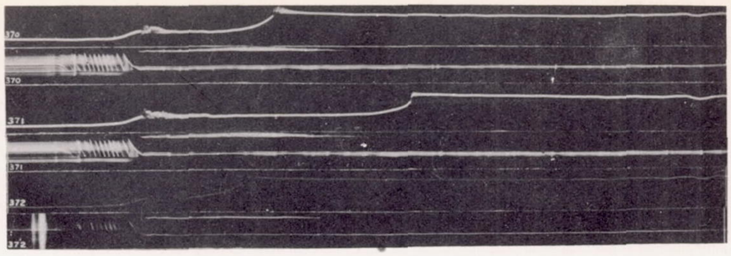
Compression ratio, 11.7



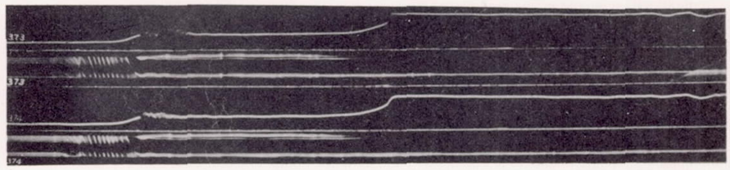
0.005 SEC

Compression ratio, 11.5

Figure 23.- Explosion records obtained with the M.I.T. rapid compression machine for triptane at various compression ratios.

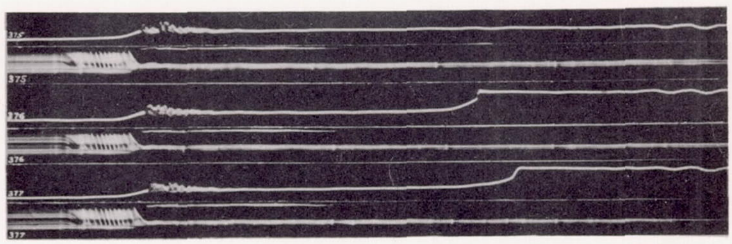


Compression ratio, 10.7



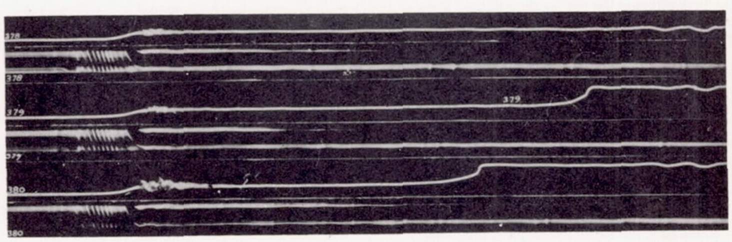
Compression ratio, 10.0

No explosion



Compression ratio, 9.4

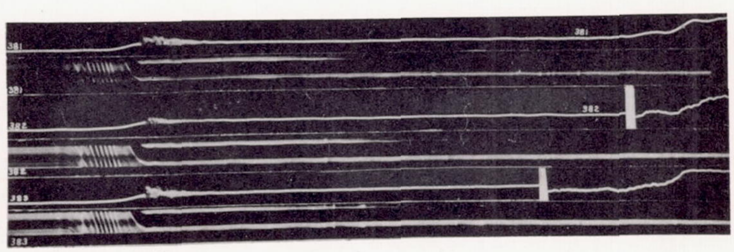
No explosion



Compression ratio, 8.9

Delay, 0.0456 sec

Delay, 0.0933 sec

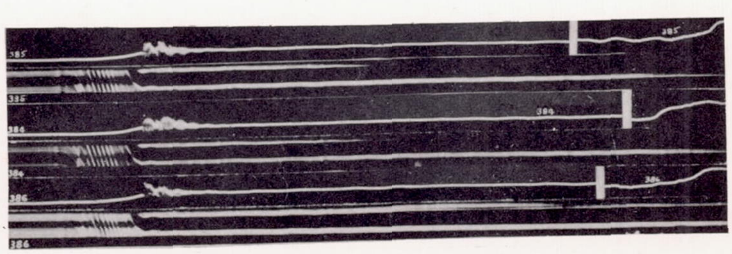


Compression ratio, 8.5

Delay, 0.0583 sec

Delay, 0.0723 sec

Delay, 0.0662 sec



0.005 SEC

Compression ratio, 8.0

Figure 24.- Explosion records obtained with M.I.T. rapid compression machine for triptane at various compression ratios.

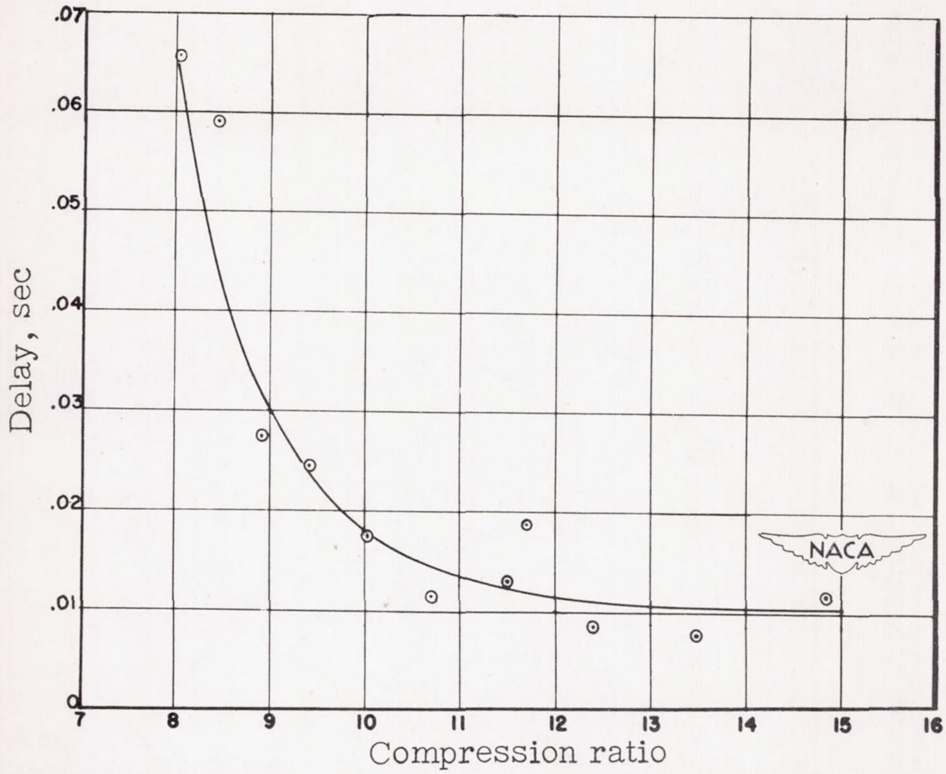
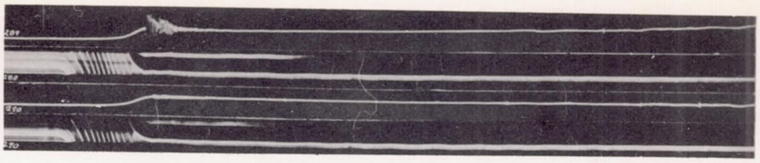


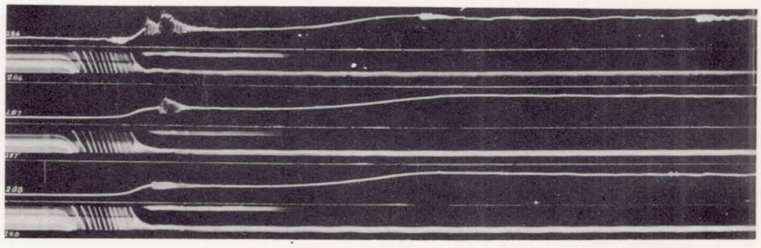
Figure 25.- Effect of compression ratio on ignition delay of triptane. Plotted points represent average values.

No explosion

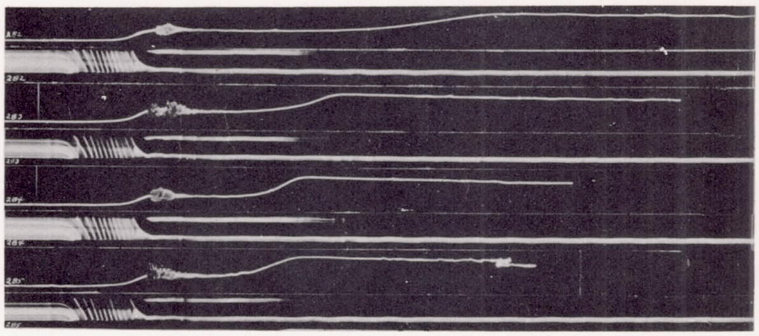
No explosion



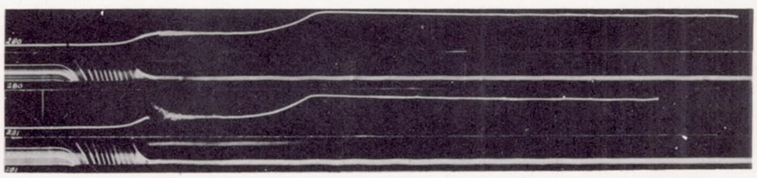
Fuel-air ratio, 0.030



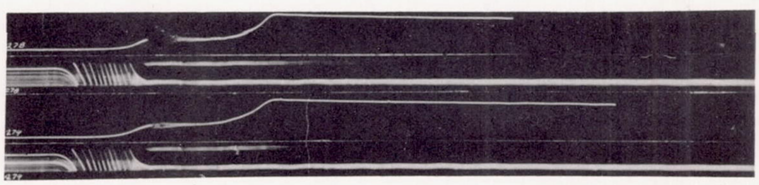
Fuel-air ratio, 0.040



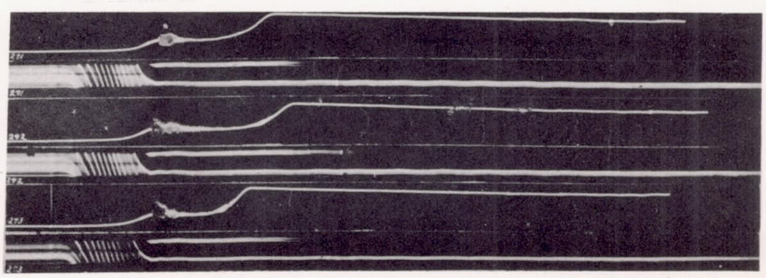
Fuel-air ratio, 0.050



Fuel-air ratio, 0.060



Fuel-air ratio, 0.076



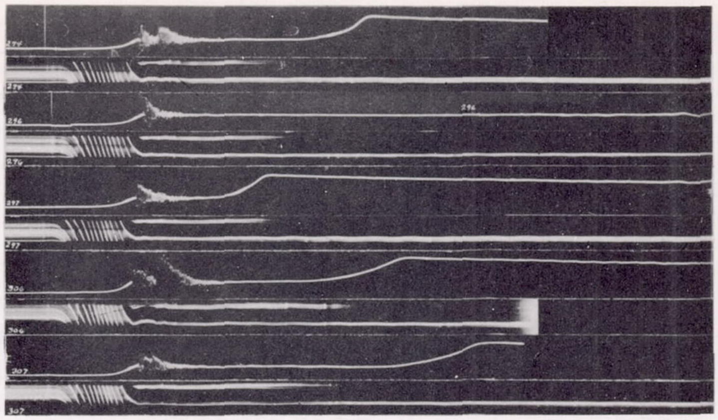
0.005 SEC

Fuel-air ratio, 0.090

Figure 26.- Explosion records obtained with the M.I.T. rapid compression machine for benzene at various fuel-air ratios.

NACA

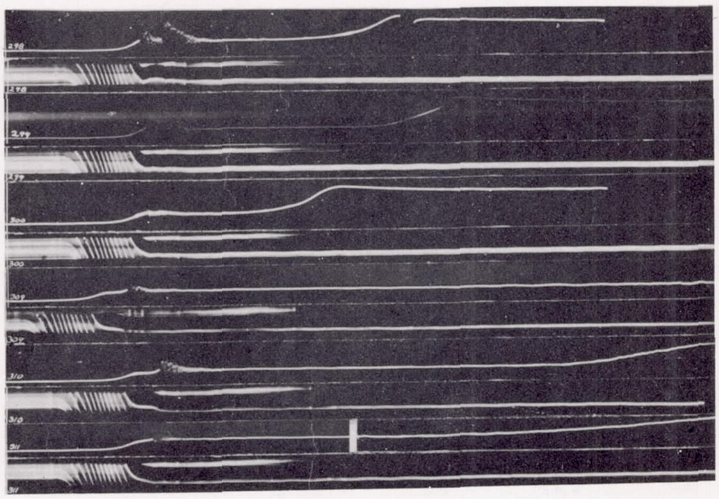
No explosion



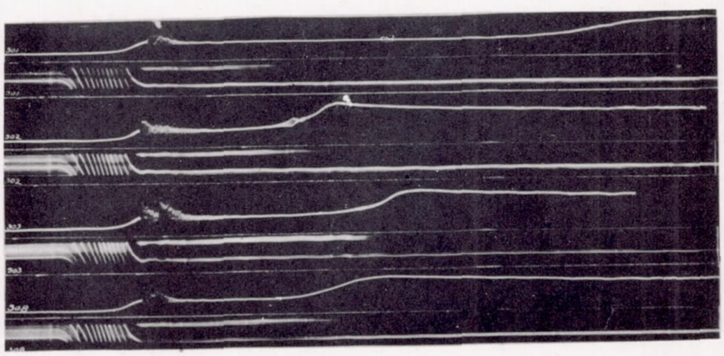
Fuel-air ratio, 0.10

No explosion

Delay, 0.065 sec



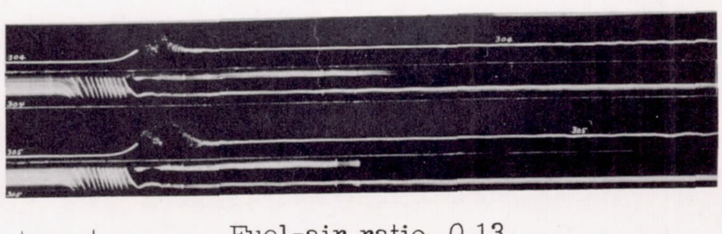
Fuel-air ratio, 0.11



Fuel-air ratio, 0.12

No explosion

No explosion



0 005 SEC

Fuel-air ratio, 0.13

Figure 27.- Explosion records obtained with M.I.T. rapid compression machine for benzene at various fuel-air ratios.

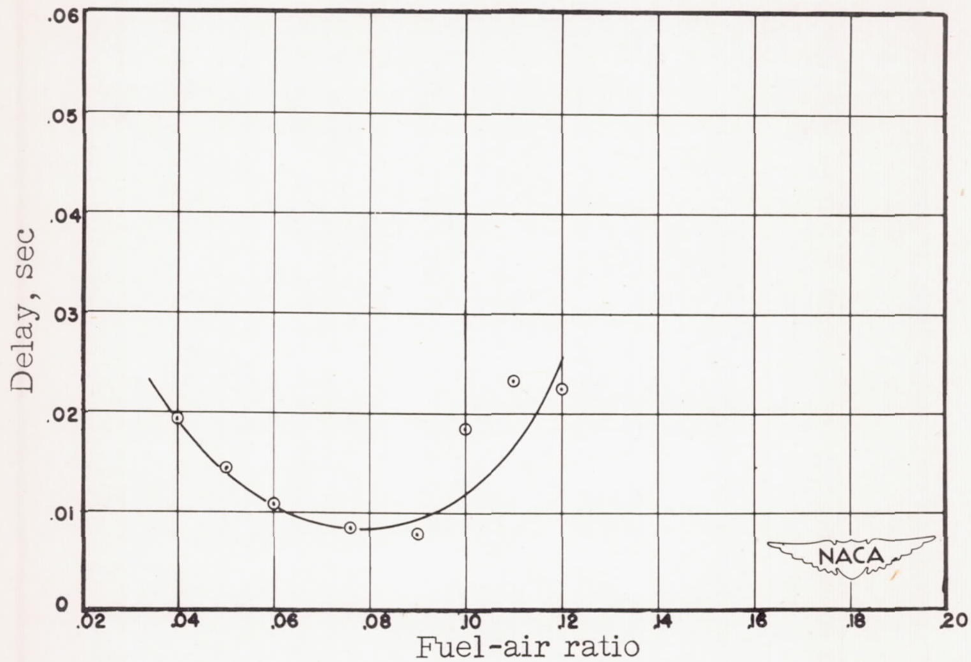
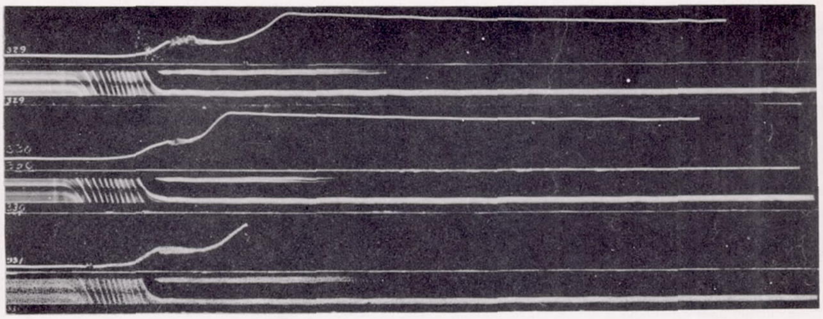
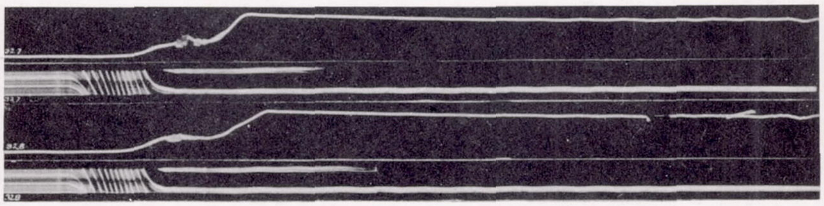


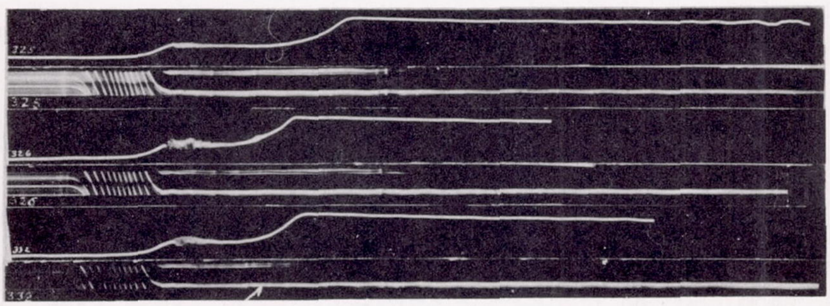
Figure 28.- Effect of fuel-air ratio on ignition delay of benzene. Plotted points represent average values.



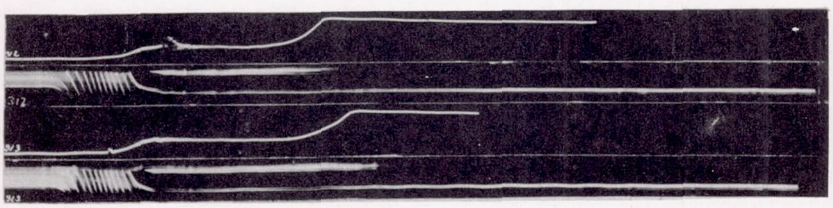
Compression ratio, 14.9



Compression ratio, 13.5



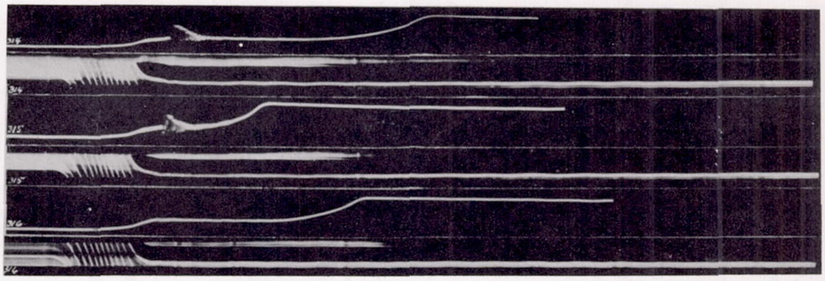
Compression ratio, 12.4



0.005 SEC

Compression ratio, 11.5

Figure 29.- Explosion records obtained with M.I.T. rapid compression machine for benzene at various compression ratios.

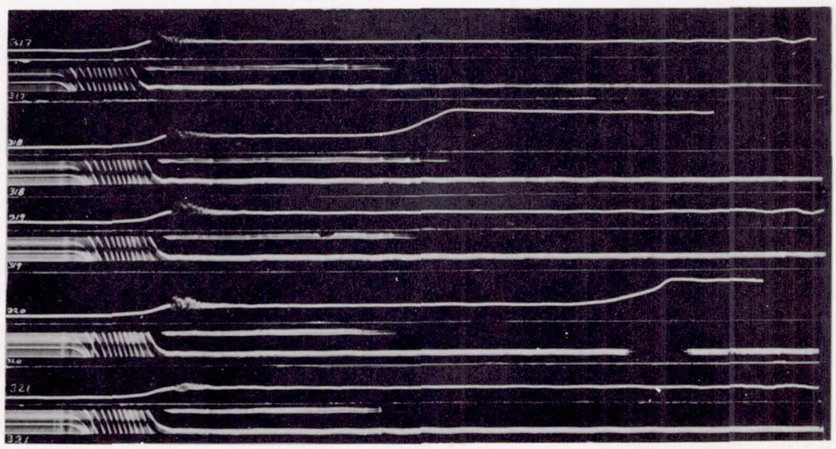


Compression ratio, 10.7

No explosion

No explosion

No explosion

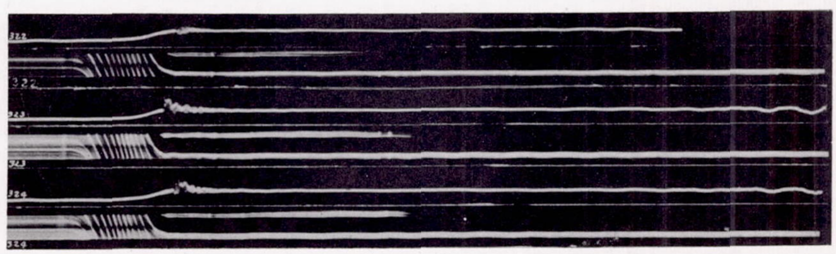


Compression ratio, 10.0

No explosion

No explosion

No explosion



0.005 SEC

Compression ratio, 9.4

Figure 30.- Explosion records obtained with M.I.T. rapid compression machine for benzene at various compression ratios.

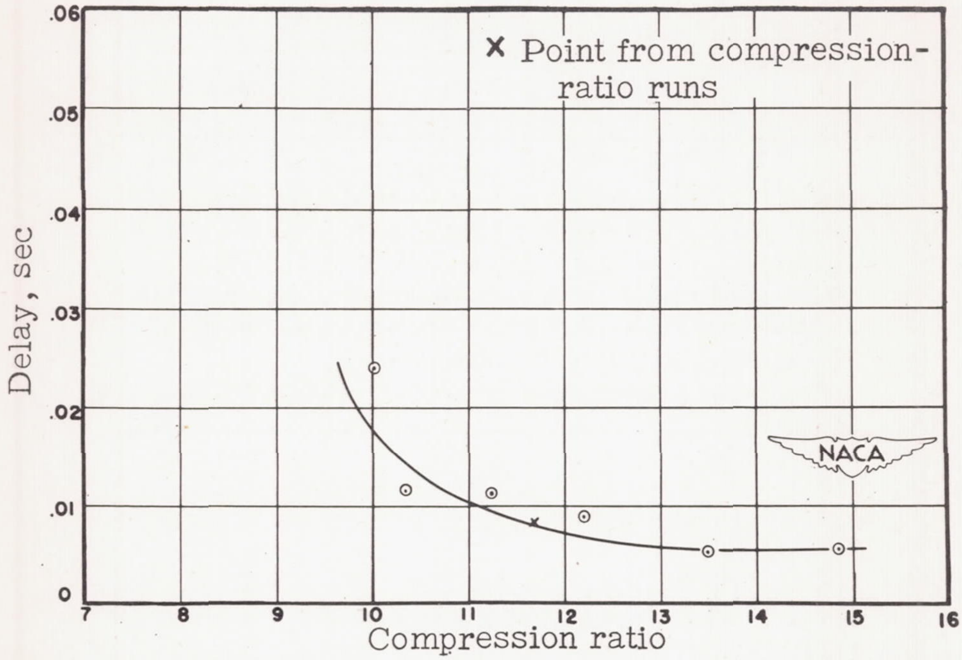


Figure 31.- The effect of compression ratio on ignition delay of benzene Plotted points are average values.

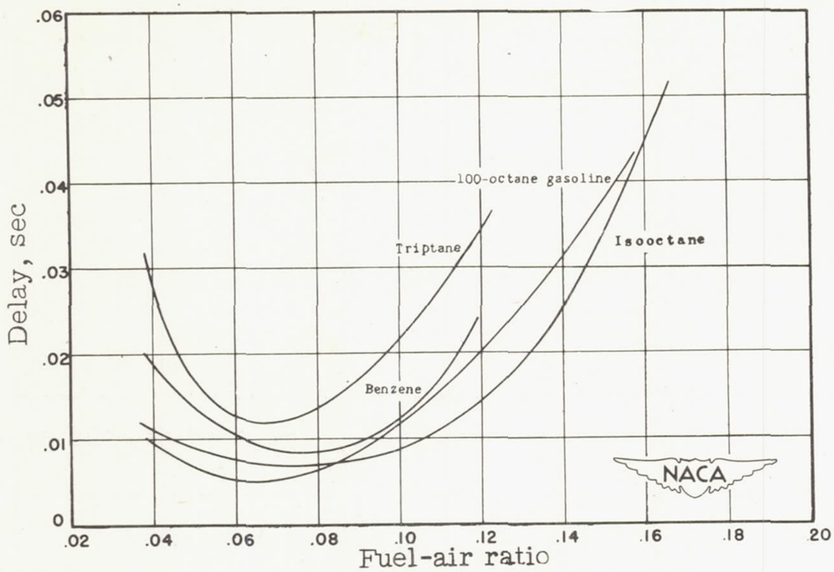


Figure 32.- Comparison of isooctane, 100-octane gasoline, triptane, and benzene with respect to variation in ignition delay with fuel-air ratio. Test conditions: compression ratio, 11.7; initial pressure, 14.7 pounds per square inch absolute; initial temperature, 149° F; compression time, approximately 0.006 second.

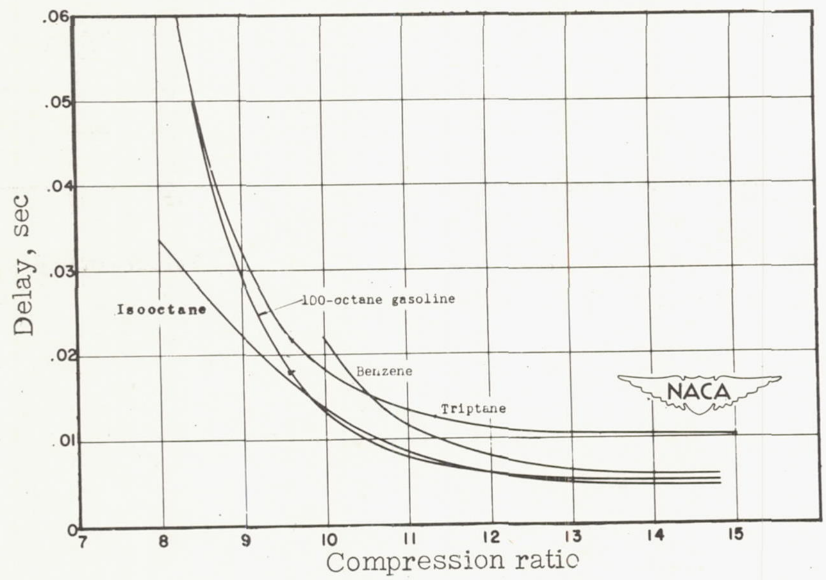


Figure 33.- Comparison of isooctane, 100-octane gasoline, triptane, and benzene with respect to variation in ignition delay with compression ratio. Test conditions: fuel-air ratio, chemically correct; initial pressure, 14.7 pounds per square inch absolute; initial temperature, 149° F; compression time, 0.006 second.

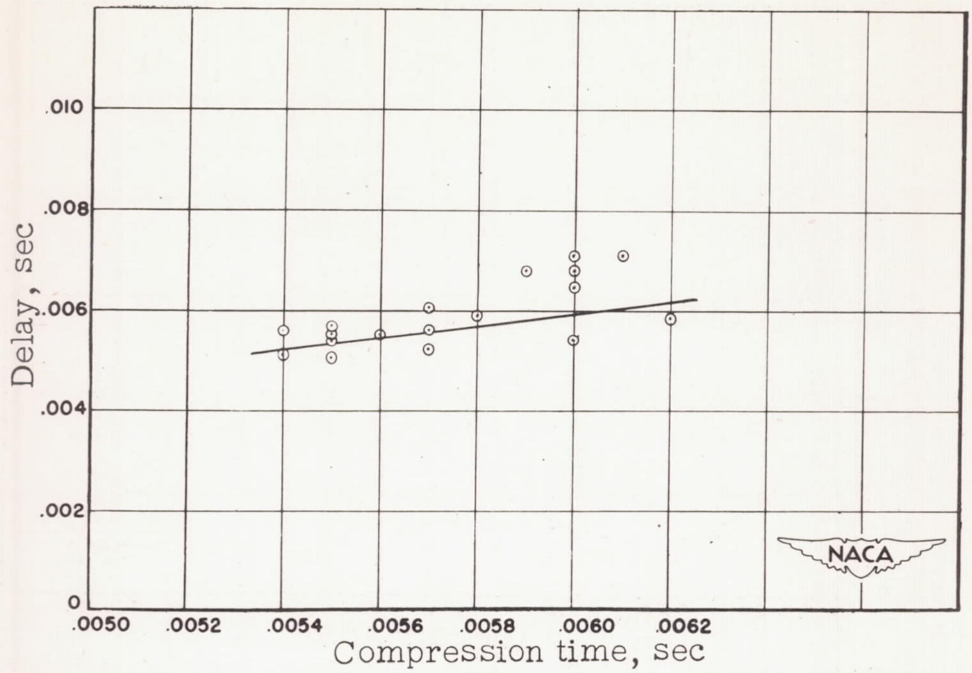


Figure 34.- Effect of compression time on ignition delay of isooctane. Fuel-air ratio, 0.067; compression ratio, 11.7.

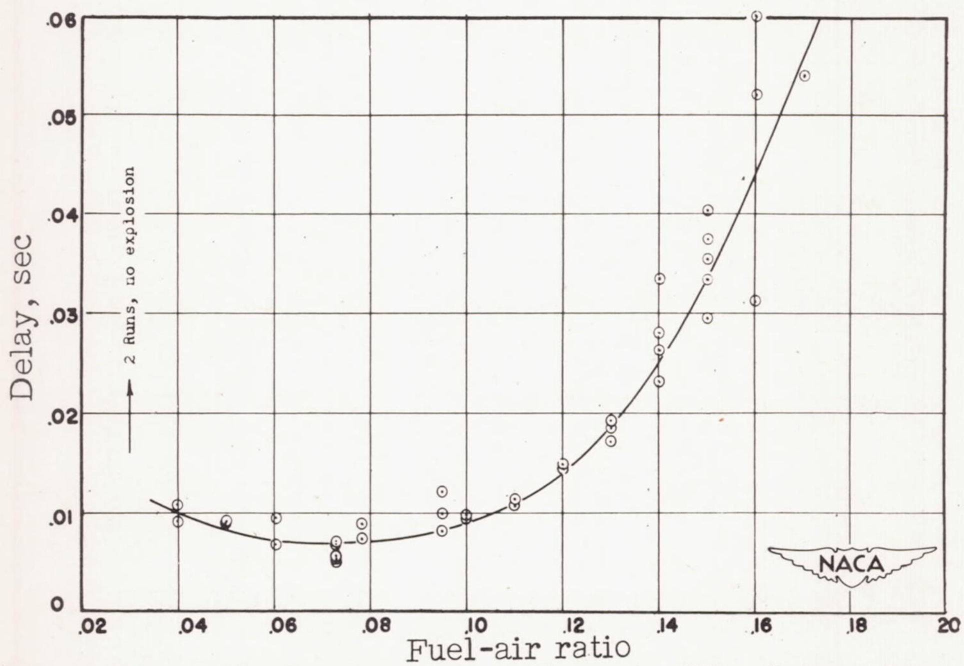


Figure 35.- Effect of fuel-air ratio on ignition delay of isooctane. Plotted points represent actual experimental values.

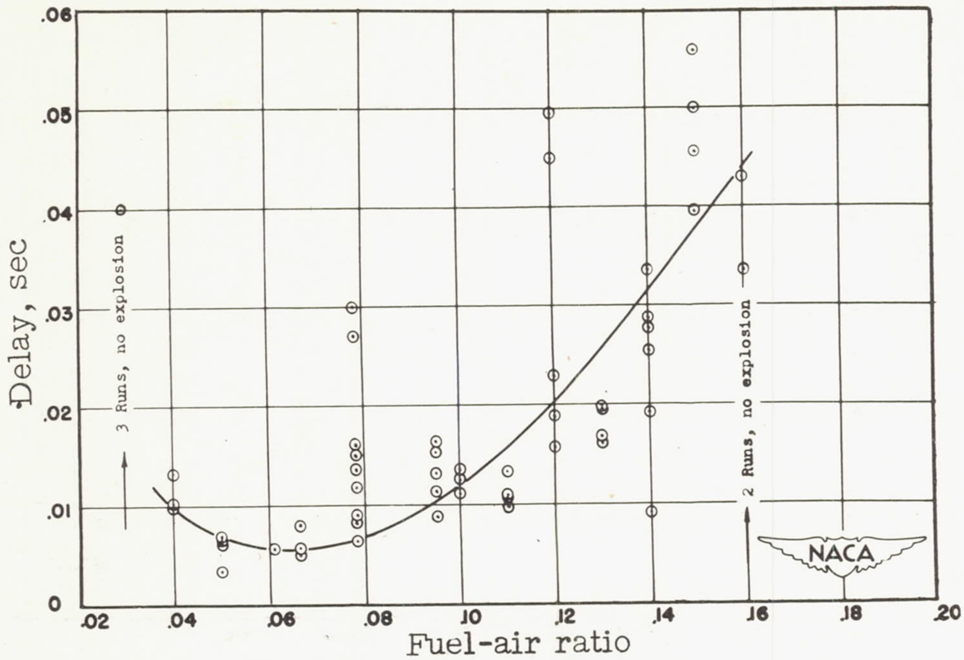


Figure 36.- Effect of fuel-air ratio on ignition delay of 100-octane gasoline. Plotted points represent actual experimental values.

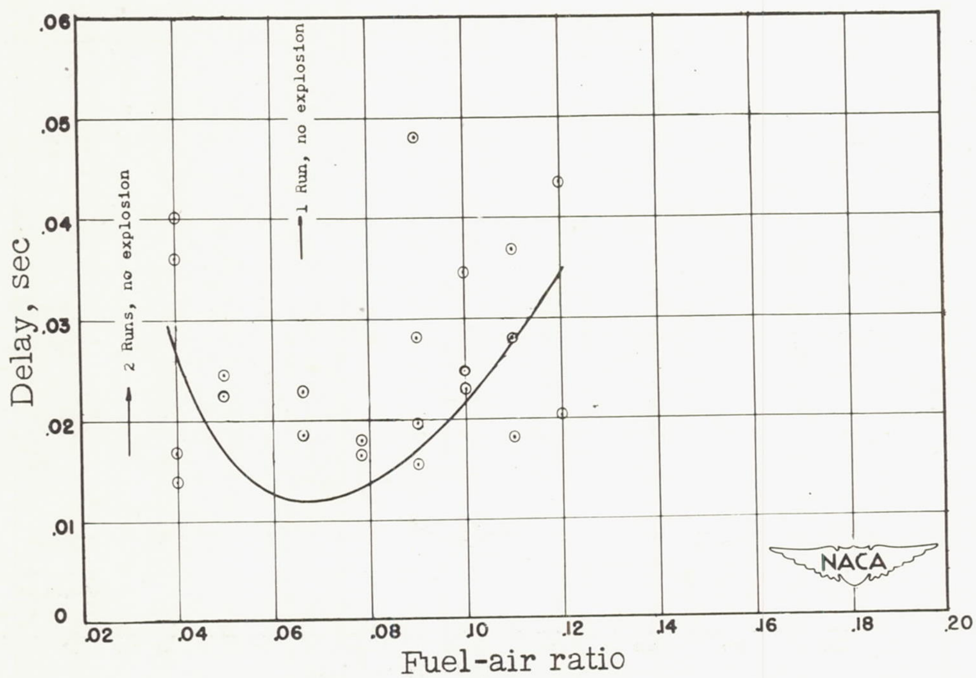


Figure 37.- Effect of fuel-air ratio on ignition delay of triptane. Plotted points represent actual experimental values.

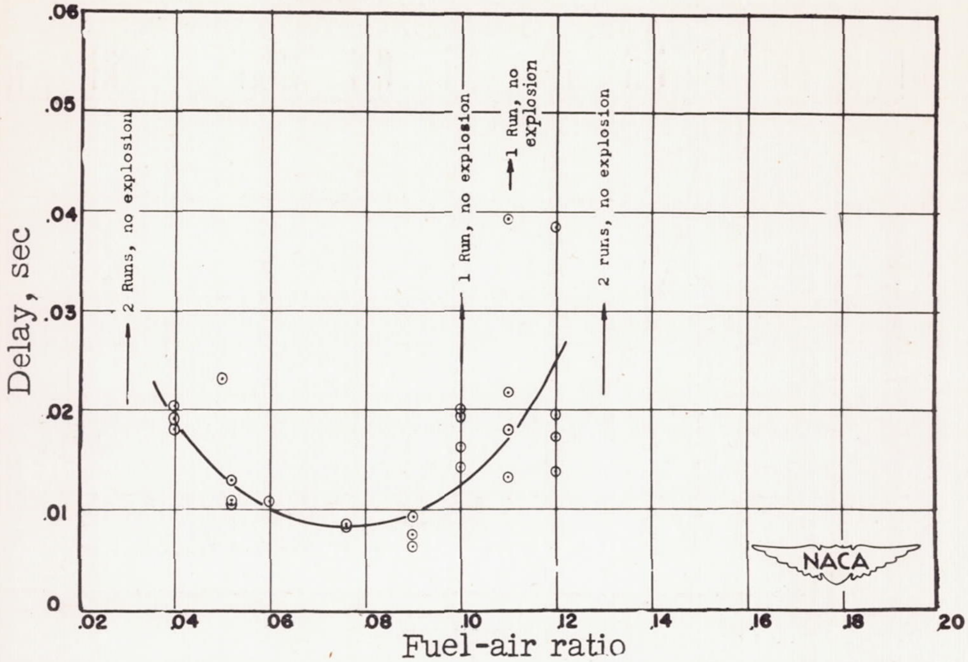


Figure 38.- Effect of fuel-air ratio on ignition delay of benzene. Plotted points represent actual experimental values.

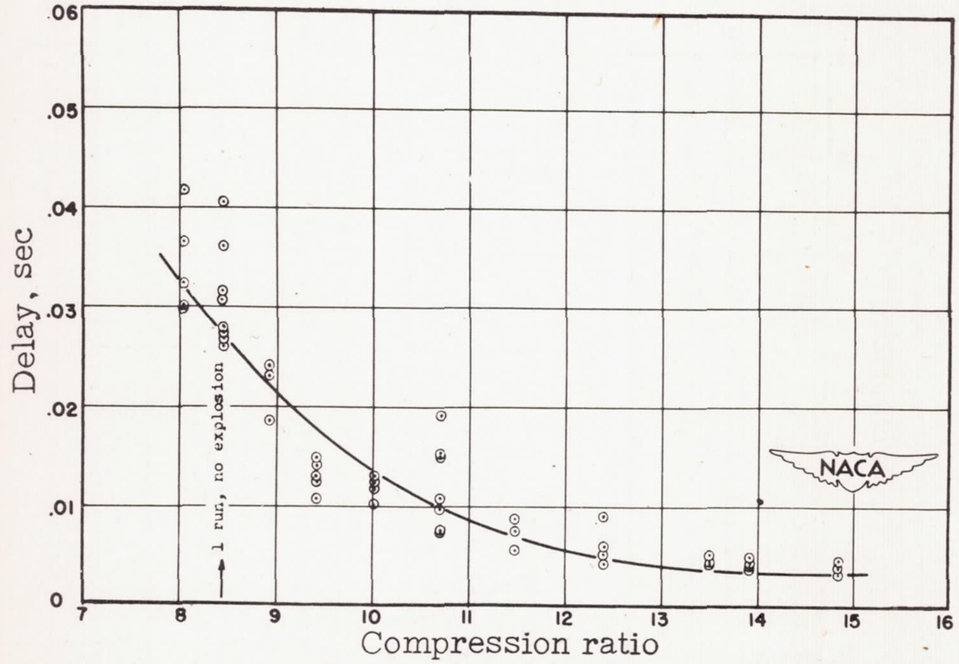


Figure 39.- Effect of compression ratio on ignition delay of isooctane. Plotted points represent actual experimental values.

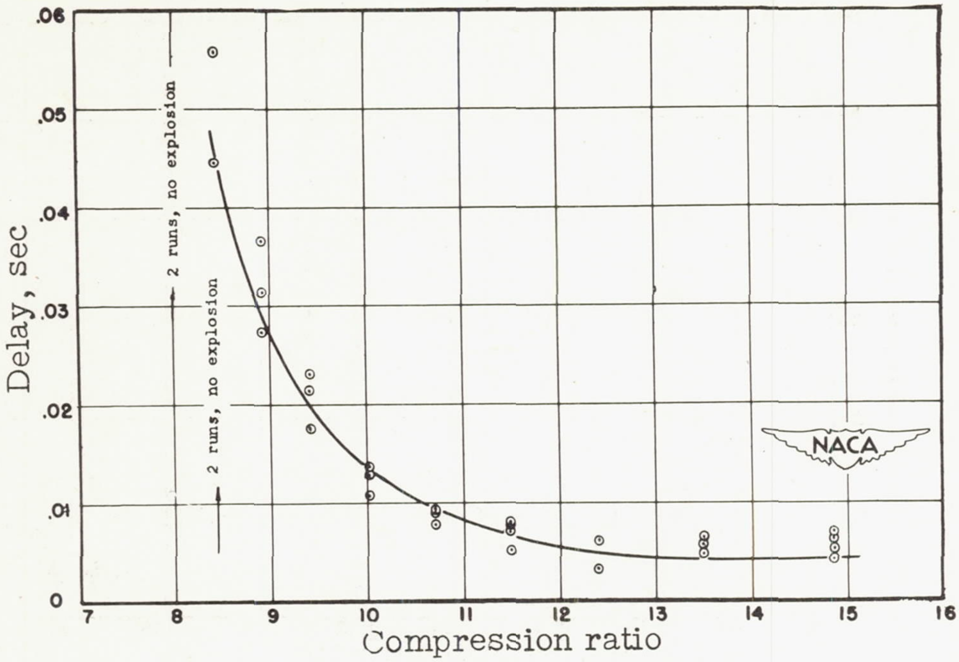


Figure 40.- Effect of compression ratio on ignition delay of 100-octane gasoline. Plotted points represent actual experimental values.

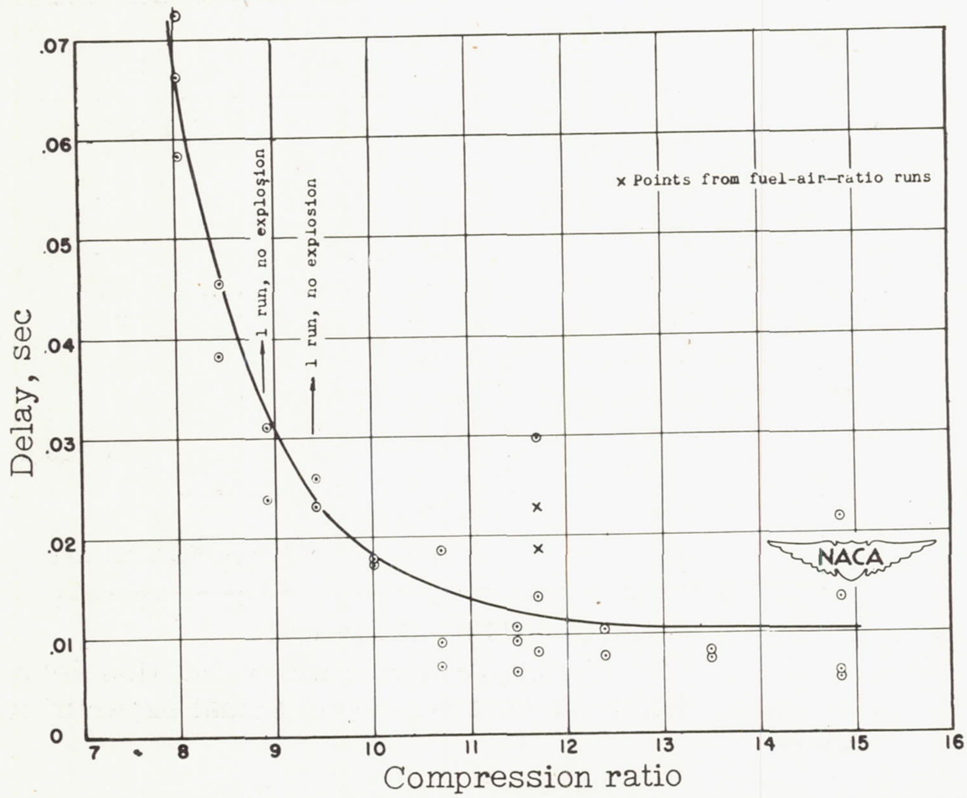


Figure 41.- Effect of compression ratio on ignition delay of triptane. Plotted points represent actual experimental values.

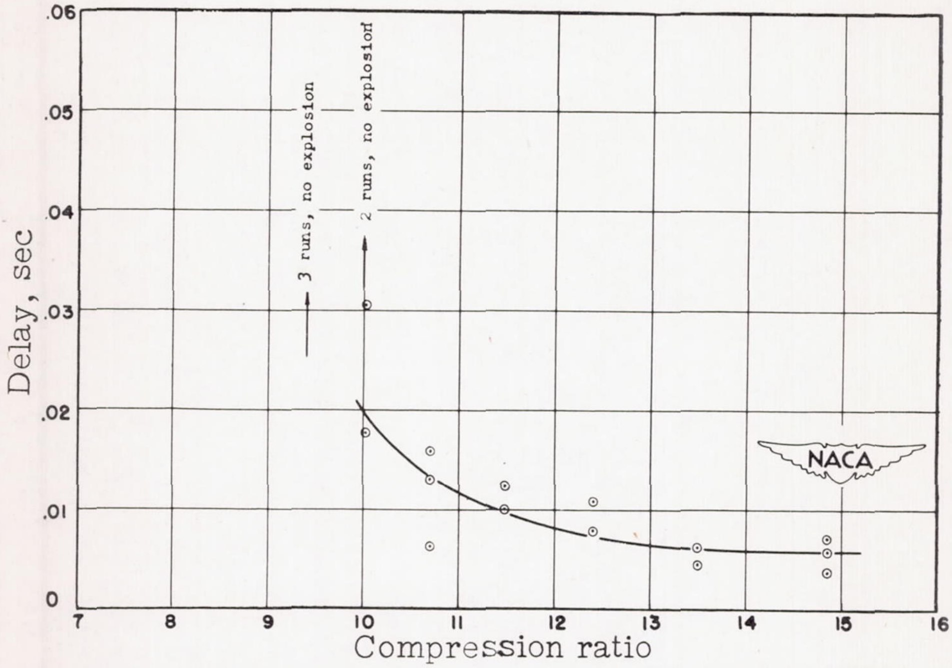
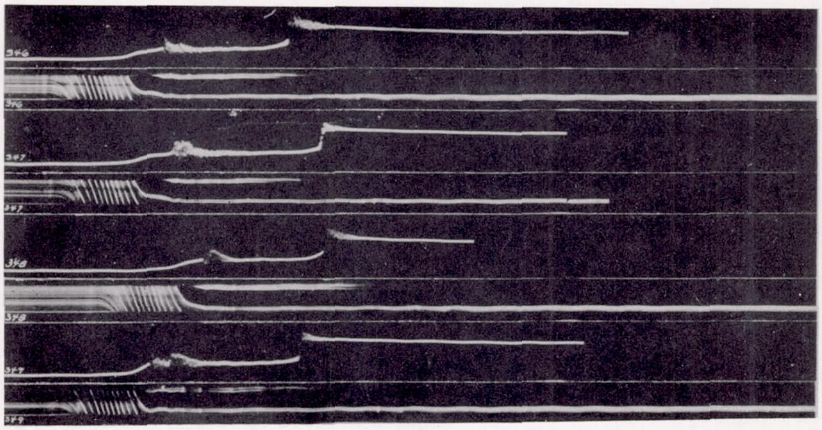
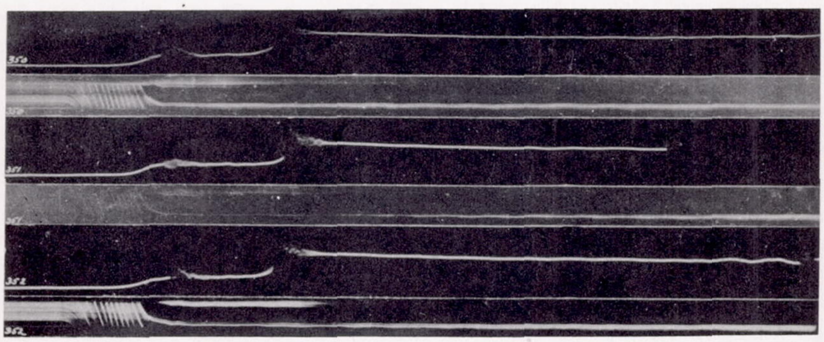


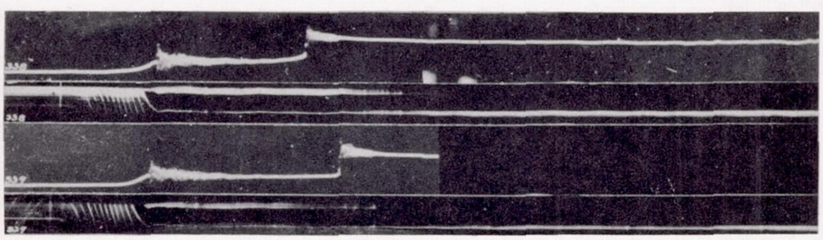
Figure 42.- Effect of compression ratio on ignition delay of benzene. Plotted points represent actual experimental values.



Dew point, -63° F



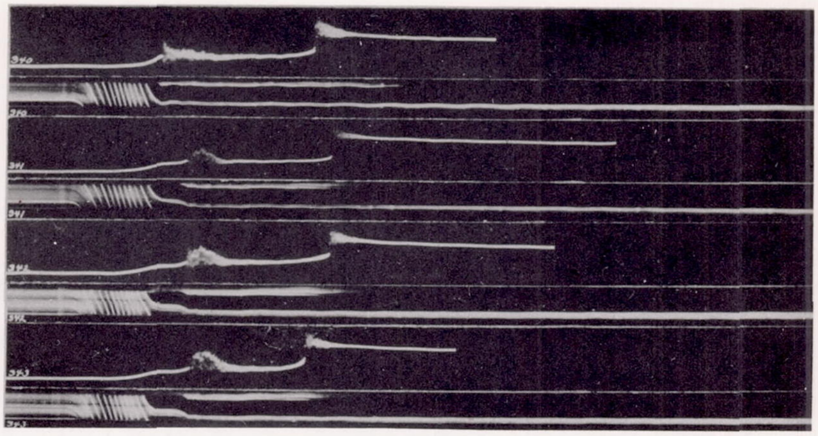
Dew point, - 49° F



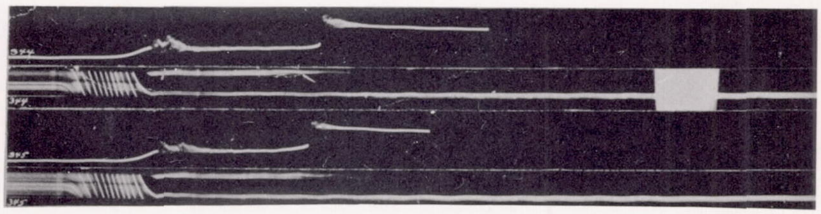
0.005 SEC

Dew point, -38° F

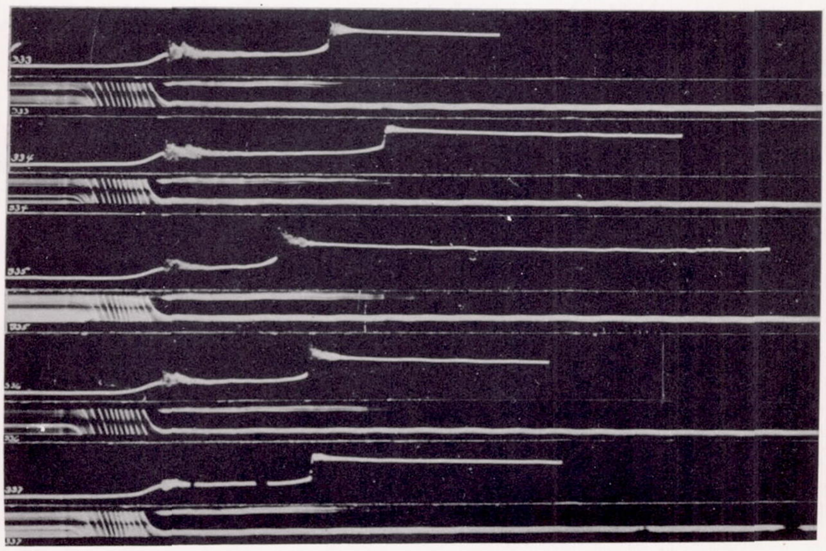
Figure 43.- Explosion records obtained with M.I.T. rapid compression machine for isooctane-air mixtures. Dew point of air varied from -63° F to -38° F.



Dew point, -11° F



Dew point, 25° F



0.005 SEC

Dew point, 60° F

Figure 44.- Explosion records obtained with M.I.T. rapid compression machine for isooctane-air mixtures. Dew point of air varied from -11° F to 60° F.

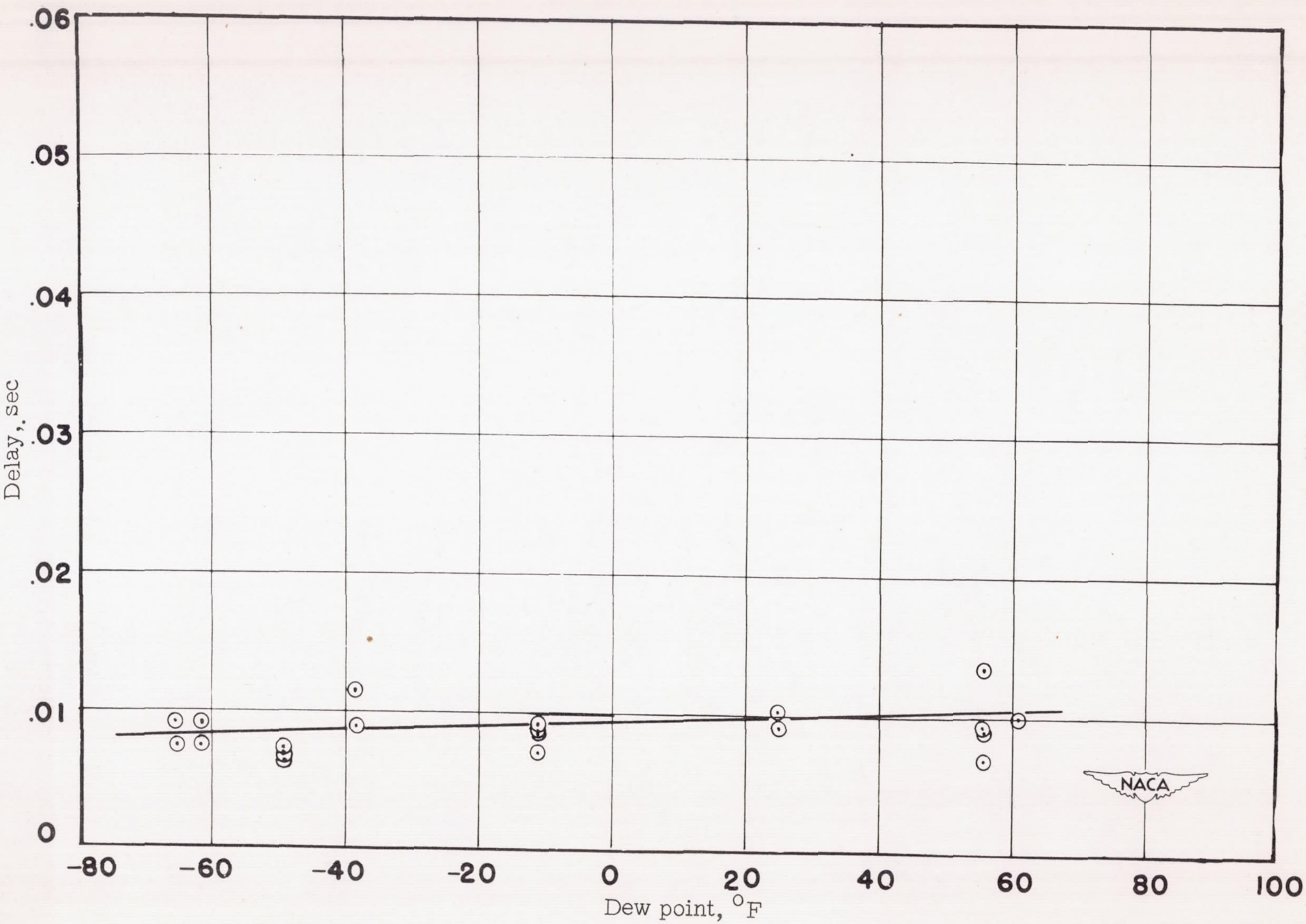


Figure 45.- Effect of air dew point on ignition delay of isooctane-air mixtures.

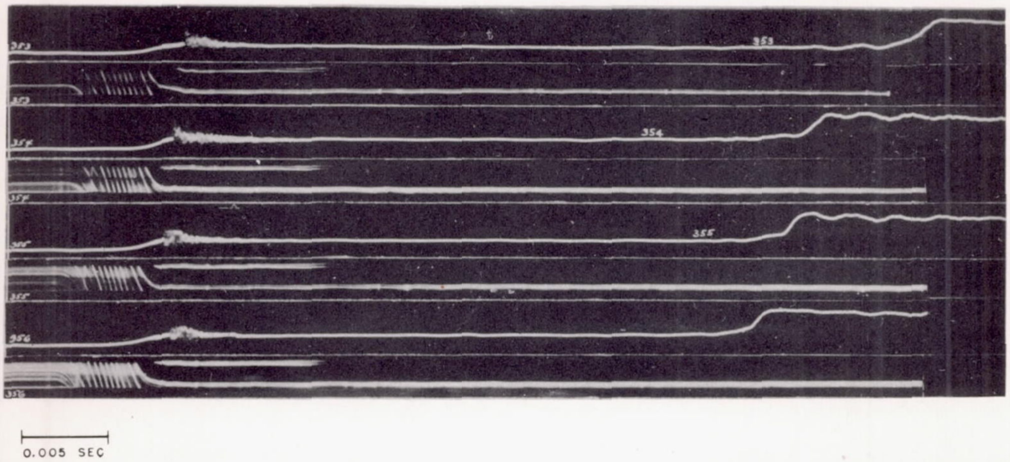
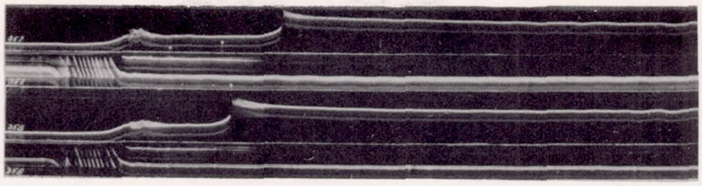
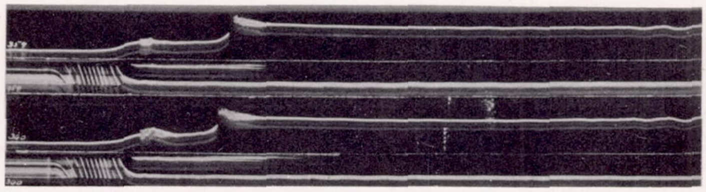


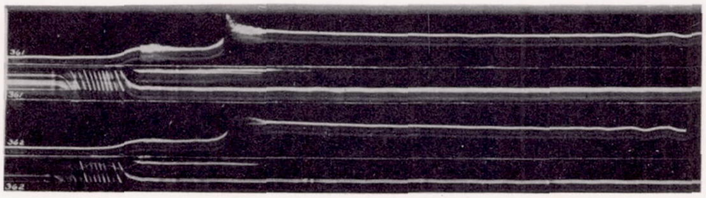
Figure 46.- Explosion records made with the M.I.T. rapid compression machine to determine the effect of saturated air on reproducibility. Fuel, isooctane; dew point of air, 68° F, fuel-air ratio, 0.16; compression ratio, 11.7.



COTTON DUST

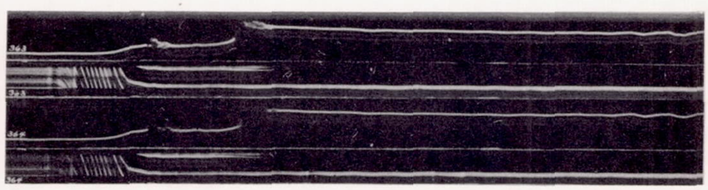


LEAD FILINGS

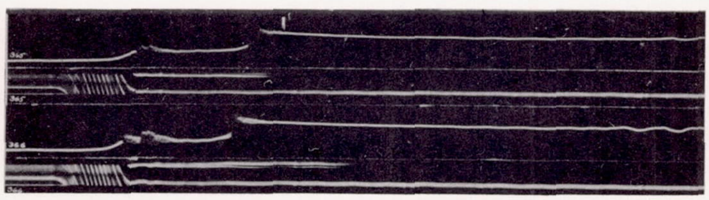


IRON FILINGS

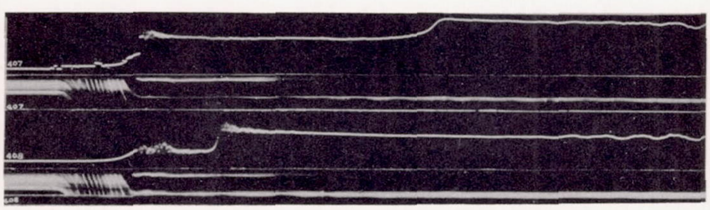
Figure 47.- Explosion records made with M.I.T. rapid compression machine to determine the effect of dust particles on reproducibility. Fuel, isooctane; fuel-air ratio, 0.067; compression ratio, 11.7.



ISOOCTANE SPRAYED ON CYLINDER WALLS



CARBON TETRACHLORIDE SPRAYED ON CYLINDER WALLS



0.005 SEC

LUBRICATING OIL SPRAYED ON CYLINDER WALLS

Figure 48.- Explosion records made with M.I.T. rapid compression machine to determine the effect on reproducibility of spraying the combustion cylinder walls with various fluids. Fuel, isooctane; fuel-air ratio, 0.067; compression ratio, 11.7.